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A Feasibility Study of a Rollover Warning Device for Heavy Trucks

J. Preston-Thomas and J.H.F. Woodrooffe

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A FEASIBILITY STUDY OF A ROLLOVER WARNING DEVICE FOR HEAVY TRUCKS

ÉTUDE DE FAISABILITÉ D'UN DISPOSITIF AVERTISSEUR DE RENVERSEMENT POUR CAMIONS LOURDS

J. Preston-Thomas
J.H.F. Woodrooffe

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

This report assesses the technical feasibility of a device that would warn the operators of heavy trucks of incipient rollover. The technical factors associated with wheel liftoff and vehicle rollover are explored. A measure known as the lateral load transfer ratio (LTR) is identified as the best parameter for predicting incipient rollover. The cost of a rollover warning device (RWD) based on LTR measurement is assessed and compared with the financial costs and rates of injuries and fatalities identified through a survey of heavy truck accidents in western Canada.

On the basis of the cost comparison, it is concluded that a stand-alone, LTR-based RWD is not feasible. However, it appears that the integration of an LTR-based device with an existing on-board weigh scale system would be cost-effective because of the substantial commonality of the two systems.

An outline of further research and development is given to establish the performance of rollover warning devices. Initially, this work would involve the instrumentation of a test vehicle and the performance of tilt-table tests. Subsequent on-road testing at a test facility would be conducted to evaluate further the performance of the devices and to define better specific rollover prediction criteria.

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16. Résumé

Le présent rapport étudie la faisabilité technique d'un dispositif qui permettrait d'avertir le conducteur d'un camion lourd de l'imminence d'un renversement. Il explore les facteurs techniques associés au soulèvement des roues et au renversement d'un véhicule. Le coefficient de transfert latéral de la charge (TLC) est reconnu comme le meilleur paramètre pour prévoir un début de renversement. Le rapport donne une évaluation du coûts d'un tel dispositif fonctionnant à partir de la mesure du transfert de la charge par rapport aux coûts et à la fréquence des accidents de camions lourds survenus dans l'Ouest canadien qui ont entraîné des blessures ou la mort.

Si l'on ne compare que les coûts, on en conclut que la mise au point d'un avertisseur autonome basé sur la mesure TLC ne serait pas rentable. Cependant, il semble qu'il soit possible d'intégrer un tel dispositif au système de pesage des camions et qu'un tel système intégré serait rentable parce que les deux dispositifs ont plusieurs caractéristiques similaires.

L'étude présente aussi l'ébauche d'un programme de recherche et développement sur les performances d'un tel dispositif. Dans une première étape, les travaux comprendraient la mise au point de l'instrumentation d'un véhicule d'essais et des paramètres d'essais sur table d'inclinaison. Ensuite, viendraient les essais sur route, dans un centre d'essais, en vue d'évaluer d'avantage le rendement du dispositif et de mieux définir les critères spécifiques de prédiction des renversements.

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FOREWORD

The work described in this report was performed by the Vehicle Dynamics Laboratory of the National Research Council Canada (NRC) in cooperation with the Transportation Development Centre (TDC) of Transport Canada (TDC Project 7258, "Development of a truck/tractor-trailer rollover threshold alarm"). TDC funding was used to support, in full, the work performed by Sparks and Berthelot (1989), while the remaining work was funded by NRC. The TDC project officer was Mr. Sesto Vespa. The project supervisor at NRC's Vehicle Dynamics Laboratory was Mr. J.H.F. Woodrooffe.

SUMMARY

The occurrence of vehicle rollover in accidents involving heavy duty truck combinations contributes substantially to injuries, fatalities and damages. This type of accident has been reported as being responsible for 95% of the incidents in which bulk spillage of hazardous commodities is involved (Ervin et al. 1980).

Vehicle design has a significant effect on an operator's ability to sense impending rollover. Where the vehicle is a tractor with two trailers (and particularly if it is an A-train, where there is no roll coupling between the two trailers), the driver may have no physical sensation of the rollover of the rear trailer until it is well past any possible recovery. Because of this lack of ability to sense rollover of the rear units of a combination vehicle, it appears reasonable to assume that the incidence of rollover might be reduced if prior warning of incipient rollover were given to the operator by a rollover warning device (RWD).

This report assesses the technical feasibility of an RWD from two directions. Initially, it reviews a survey of the costs and rates of injuries and fatalities in rollovers of heavy trucks. The costs of the rollovers that could be avoided by using an RWD are used to estimate the amount that an operator could afford to invest in such a device.

The report then assesses the feasibility of an RWD from the opposite direction by exploring the technical factors associated with wheel lift-off and vehicle rollover, and it identifies a specific approach for predicting incipient rollover. The cost of a device based on this approach is estimated and compared with the return-on-investment amount identified in the accident survey. The probable design features of the device are explored and an outline of further research and development is given to establish the performance of RWDs.

The accident survey referred to above was conducted by Sparks and Berthelot (1989). They found that vehicle rollover occurred in 23% of 661 accidents involving heavy trucks from four fleets operating in western Canada and the northwest U.S. over a four-year period. Of these rollover accidents, only 3% were identified as having definitely been preventable by a rollover warning device (RWD). Those classified as potentially-preventable (depending on the performance of the device and of the vehicle operator) accounted for 38% of the total. The non-preventable and unknowns accounted for the remaining 59%. While the rollover accidents accounted for only 23% of the total number of accidents, they accounted for 62% of the total damages, 29% of the number of injuries and 29% of the number of fatalities.

For the vehicles in the Sparks and Berthelot study, the average annual damage per vehicle resulting from rollovers that were judged preventable by an RWD was $42. If an RWD could also prevent 25% of the potentially-

preventable accidents, then the average annual damage per vehicle that would be prevented by an RWD would rise to $176. With this additional saving, it was determined that a vehicle life of 5 years and an interest rate of 12% would lead to an economic breakeven cost for an RWD bought with a new vehicle of $633.

The use of RWDs could be expected to affect the injury and fatality rates as well. If all 661 vehicles in the Sparks and Berthelot study had been equipped with an RWD that eliminated all of the preventable rollovers and 25% of the potentially-preventable rollovers, then over the four-year period of the survey the total number of injuries would have been 91 instead of 93, and the total number of fatalities would have been 34 instead of 35.

The lateral load transfer ratio (LTR) is a measure able to provide a relatively continuous, normalized indication of how close a vehicle is to rollover, regardless of the vehicle payload and CG location and height. However, while the LTR is a useful indicator of incipient rollover, on-road measurement of it is not trivial. A method is proposed whereby load cells mounted close to the suspension of one or more axles could be used for estimating the LTR. While it would be desirable to measure wheel loads for defining the LTR on all axles but the steering axle, priority would be given to the rear-most axles on the vehicle. Signals from the load cells would be transmitted to a cab-mounted display that would process them and provide a suitable warning when required.

Because of the similarities between the components of an LTR-based RWD and those of existing on-board weigh scale systems, it is reasonable to expect their costs would also be similar, i.e., in the range of $4000 to $6000 – clearly beyond the RWD breakeven cost of $633 identified above. This cost would be particularly difficult for a vehicle owner to justify exclusively for an RWD because the damage costs from rollover accidents are relatively intangible to individuals. However, because of the component similarity, it should be possible to develop a system combining the functions of an on-board weigh scale system and an RWD at minimal incremental cost. Such a device would result in a higher return-on-investment for the owner than could be obtained if the RWD were marketed on its own.

A follow-up workplan is suggested to investigate the practical potential of the LTR as a basis for the prediction of rollover. This workplan would involve equipping a test vehicle with the transducers and then performing a series of tilt-table tests. The rollover predictions from the on-board transducers would be compared with the vehicle's actual roll performance. If this assessment were positive, then the test vehicle would be modified with roll-restricting outriggers and additional instrumentation for on-road testing at a test facility. Subsequent tests would further establish the performance potential of LTR-based rollover prediction and would allow further investigation and refinement of the specific prediction criteria.

SOMMAIRE

Les accidents routiers impliquant le renversement d'un ensemble de véhicules lourds causent un nombre important de blessures et de victimes ainsi qu'une quantité importante de dommages. 95% des accidents routiers causant un déversement en vrac de matières dangereuses sont des accidents avec renversement (Ervin et al. 1980).

La conception des véhicules a un effet important sur la capacité que peut avoir un conducteur de sentir un renversement imminent. Lorsque l'ensemble de véhicules est composé d'un tracteur et de deux remorques (plus particulièrement lorsqu'il s'agit d'un train double de type A dans lequel il n'y a pas d'accouplement en torsion entre les deux remorques) il est possible que le conducteur ne sente qu'il y a renversement de la remorque arrière qu'au moment où il est beaucoup trop tard pour corriger la situation. À cause de cette incapacité de sentir le renversement des remorques arrières d'un ensemble de véhicules, il semble qu'il soit raisonnable de supposer que le nombre de renversements pourrait être diminué si le conducteur était averti à l'avance d'un renversement imminent au moyen d'un dispositif d'avertissement de renversement (DAR).

Le présent rapport traite des possibilités techniques de concevoir un DAR, selon deux orientations différentes. Il traite d'abord des résultats d'une enquête sur le nombre de blessures et de victimes causées par les renversements de camions lourds et des coûts s'y rattachant. Les coûts associés aux renversements qui pourraient être évités par un DAR sont utilisés pour calculer le montant qu'un conducteur pourrait se permettre d'investir dans un tel dispositif.

Le rapport traite ensuite des possibilités de concevoir un DAR en prenant une orientation entièrement différente en examinant les facteurs techniques associés au soulèvement des roues et au renversement du véhicule. Le rapport fournit une approche précise pour prédire les renversements imminents et le coût d'un dispositif, établi selon cette approche, est calculé et comparé au taux de rendement du capital investi fournit par l'enquête sur les accidents. Des caractéristiques de conception potentielles du dispositif sont étudiées et un plan de recherches et de développements futur pour déterminer le rendement des DAR est donné.

L'enquête sur les accidents dont il est question ci-dessus a été menée par Sparks et Berthelot (1989). Ils ont découvert qu'il y avait eu un renversement dans 23% des 661 accidents qui se sont produits sur une période de quatre ans et qui impliquaient des camions lourds de quatre flottes de l'ouest du Canada et du nord-ouest des États-Unis. De ces accidents avec renversement, 3% seulement ont été identifiés comme ayant «définitivement pu être évités» par un DAR et 38% ont été classés comme ayant «peut-être pu être évités» (selon le rendement du dispositif et du conducteur du véhicule). Les 59% restant correspondent à des accidents qui n'auraient pas pu être évités et à des inconnus. Même si les accidents avec renversement ne correspondaient qu'à 23% du nombre total

des accidents, ils correspondaient à 62% des dommages, 29% du nombre de blessures et 29% du nombre de victimes.

Pour les véhicules de l'étude de Sparks et Berthelot, le coût annuel moyen des dommages par véhicule par suite d'un renversement qui aurait pu être évité par un DAR, est de 42$. Si un tel dispositif pouvait aussi empêcher 25% des accidents considérés comme pouvant peut-être être évités, le coût annuel moyen des dommages par véhicule qui pourraient être évités par un DAR s'élèverait alors à 276$. En tenant compte de cette économie additionnelle, il a été calculé qu'avec une durée de vie de 5 ans et un taux d'intérêt de 12% on obtiendrait un coût de rentabilité économique de 663$ pour un DAR acheté avec un nouveau véhicule.

L'utilisation d'un DAR pourrait aussi diminuer le nombre de blessures et de victimes. Si les 661 véhicules de l'étude de Sparks et Berthelot avaient été équipés d'un DAR qui aurait permis d'éviter tous les renversements pouvant être évités, et 25% des renversements pouvant peut-être êtres évités, le nombre de blessures et de victimes aurait été respectivement de 91 au lieu de 93 et de 34 au lieu de 35 pour la période de quatre ans qu'à duré l'étude.

Le taux de transfert des charges latérales est une mesure qui permet d'indiquer de façon relativement continue et sur un échelle standardisée si un véhicule est près ou non de renverser, peu importe la charge utile du véhicule et l'emplacement et la hauteur du centre de gravité. Malgré le fait que le taux de transfert des charges latérales est soit étroitement lié au seuil de renversement du vehicule, en pratique, l'évaluation de ce taux n'est pas chose facile.

La méthode qui est proposée consiste à placer des boites dynamométriques près de la suspension d'un essieu ou de plusieurs essieux et de les utiliser pour calculer le taux de transfert des charges. Même s'il est souhaitable de connaitre la mesure de la charge sur les roues pour définir le taux de transfert des charges sur tous les essieux à l'exception de l'essieu directeur, la priorité devrait être donnée aux essieux les plus à l'arrière du véhicule. Les signaux des boites dynamométriques seraient transmis à un affichage placé dans la cabine qui les traiterait et fournirait un avertissement efficace au besoin.

À cause des ressemblances entre les composantes d'un DAR basé sur le taux de transfert des charges et ceux d'un système de balance à bord, il est raisonnable de prévoir que leurs coûts seraient semblables, soit entre 4 000$ et 6 000$, ce qui est nettement au-dessus du coût de rentabilité du DAR de 633$ donné plus haut. Ce coût serait particulièrement difficile à justifier seulement pour un DAR car les propriétaires de véhicules ne sont pas sensibilisés aux coûts des dommages causés par les accidents avec renversement. Cependant, à cause de la similitude des dispositifs, il devrait être possible de mettre au point un système qui combinerait les fonctions d'un système de balance et d'un DAR à un coût supplémentaire minimal. Un tel dispositif

donnerait un meilleur taux de rendement de capital investi au propriétaire que si le DAR était vendu séparément.

Un plan du travail de suivi est suggéré pour étudier les possibilités véritables qu'offre le taux de transfert des charges en tant qu'élément de base pour prédire les renversements. Ce plan de travail impliquerait de doter un véhicule d'essai de transducteurs et d'effectuer ensuite une série d'essais sur une table d'inclinaison. Les prédictions de renversement obtenus des transducteurs de bord seraient comparées au rendement de roulis du véhicule. Si cette évaluation était positif, le véhicule d'essais serait alors modifié et doté de stabilisateurs de roulis et d'autres instruments pour des essais sur route à une installation d'essais. Des essais supplémentaires permettraient de mieux déterminer le potentiel de rendement de la prédiction du renversement basé sur le taux de transfert des charges et permettraient une étude et une mise au point plus approfondie des critères spécifiques de prédiction.

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LIST OF SYMBOLS

Symbol		Units
a_y	Lateral acceleration (parallel to the road surface)	m/s^2
F_i	Vertical reaction on the wheels on the inside of a turn	N
F_o	Vertical reaction on the wheels on the outside of a turn	N
g	Acceleration due to gravity	m/s^2
h	Difference between sprung and unsprung mass heights	m
h_r	Height of roll centre	m
h_s	Height of sprung mass	m
h_u	Height of unsprung mass	m
k	Roll stiffness of the sprung mass relative to the unsprung mass due to the vertical stiffness of both suspension springs on an axle	N-m/rad
k_{aux}	Roll stiffness of the sprung mass relative to the unsprung mass due to all effects other than those contributing to k	N-m/rad
k_r	Composite roll stiffness due to both k_r and k_{aux}	N-m/rad
k_s	Linear stiffness of a suspension spring on one side of the axle	N/m
k_t	Linear stiffness of a dual tire	N/m
S_u	Lateral offset of the unsprung mass from the centreline	m
S_r	Lateral offset of the roll centre from the centreline	m
S_s	Lateral offset of the sprung mass from the centreline	m
T	Half of the distance from the centre of one dual tire to the centre of the other dual tire	m
T_s	Lateral spring spacing	m
W_s	Weight of sprung mass	N
W_u	Weight of unsprung mass	N
δ	Tire deflection	m
δ_0	Tire deflection when φ_u=0	m
φ_u	Roll angle of the unsprung mass relative to the road surface	rad
φ_s	Roll angle of the sprung mass relative to the road surface	rad

1.0 INTRODUCTION

The occurrence of vehicle rollover in accidents involving heavy duty truck combinations contributes substantially to injuries, fatalities and damages. This type of accident has been reported as being responsible for 95% of the incidents in which bulk spillage of hazardous commodities is involved (Ervin et al. 1980).

A vehicle's roll stability can be represented quantitatively by its rollover threshold. In simple terms, this is the maximum lateral acceleration to which the vehicle can be subjected without rolling over. The value is usually expressed in units of gravitational acceleration (i.e., in "g's", where 1 g = 9.81 m/s^2).

The rollover threshold of a heavy duty articulated vehicle is strongly related to its payload centre of gravity (CG) height. Figure 1 shows examples of this relationship for two tractor-semitrailers and for two double combination vehicles, as reported by Ervin (1983). For each vehicle, the figure shows that the rollover threshold decreases by approximately 0.05 g for each 10-inch (25 cm) increase in the payload CG height.

The correlation between the rollover threshold and the occurrence of rollover in single-vehicle heavy truck accidents is also very high. Figure 2 shows the percentage of rollovers that occurred in a sample of tractor-semitrailer single-vehicle accidents as a function of the rollover threshold of the vehicles. The graph, which is based on accident data from the Bureau of Motor Carrier Safety (BMCS) of the U.S. Department of Transportation collected from 1976 to 1979, represents 9000 single-vehicle accidents involving three-axle tractors pulling two-axle, van-type semitrailers. Of these 9000 accidents, more than 2000 (i.e., more than 22%) involved rollover. Rollover thresholds were estimated for each of the 9000 vehicles from the reported gross vehicle weight at the time of the accident. As shown in the figure, fully-loaded vehicles with rollover thresholds of approximately 0.4 g are almost ten times as likely to roll over in an accident as empty vehicles with rollover thresholds of approximately 0.65 g.

The influence of CG height extends even to passenger cars, which normally have much higher rollover thresholds than heavy trucks. A recent study performed in the U.S. (Mengert et al. 1989) found that, of 39000 single-vehicle accidents involving passenger cars and light utility vehicles, 4910 (12.6%) involved rollover. The study attempted to correlate the rollover accidents with various vehicle factors, such as the wheelbase and the stability factor (defined as one-half of the track width divided by the centre of gravity height), and with accident factors related to the driver (alcohol involvement, age, etc.) and the operating environment (road curvature, weather, etc.). The study found that the prediction of rollover (vs. non-rollover) correlated much more strongly with the stability factor than with any other. With the stability factor included in a regression model, the index of agreement

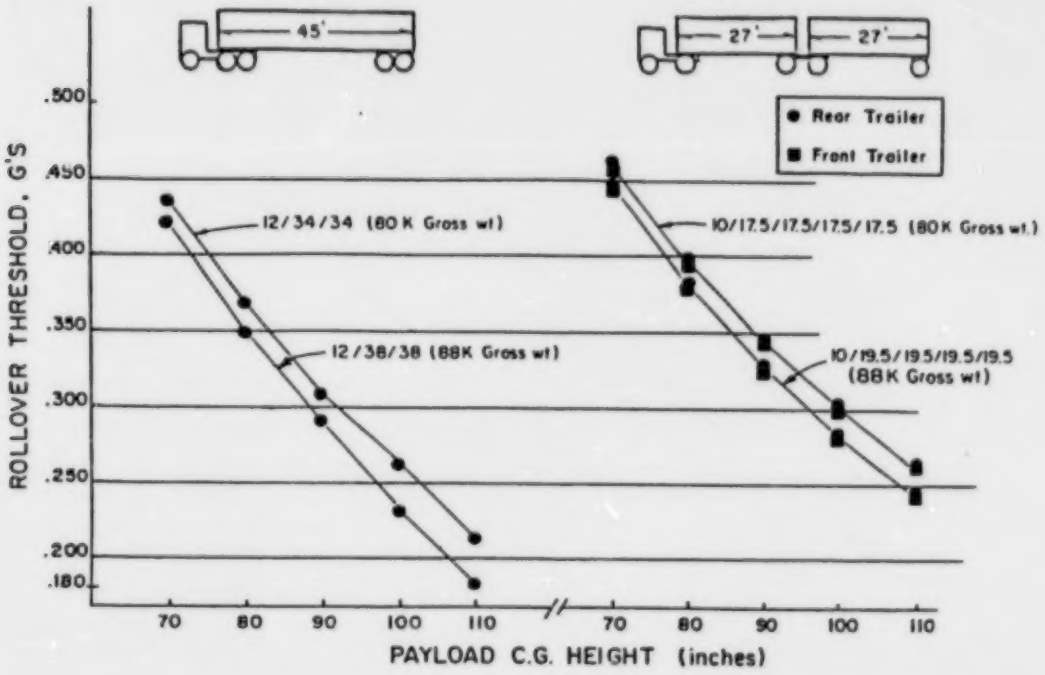

Figure 1 The influence of payload CG height on rollover threshold (from Ervin 1983).

(r^2) exceeded 0.9; without it the value dropped to 0.53. In fact, a better correlation could be obtained by using the stability factor alone than by using all of the other factors together in the absence of the stability factor. This underscores the significance of the rollover threshold.

It is clear that rollovers are involved in a significant proportion of single-vehicle accidents, and that trucks with high CG heights are particularly susceptible to rollover. While a reduction in the mean CG height of vehicles is clearly one method of reducing the incidence of rollover, there is reason to believe that the ability of operators to recognize impending rollover of their vehicles is also important.

The ability of vehicle operators to sense impending rollover is variable and often inconsistent. Vehicle design has a significant effect on the operator's ability to sense it. Where the vehicle is a tractor with two trailers (and particularly if it is an A-train, where there is no roll coupling between the two trailers), the driver may have no physical sensation of the rollover of the rear trailer until it is well past any possible recovery. Because of this lack of ability to sense rollover of the rear units of a combination vehicle, it appears reasonable to assume that the incidence of rollover might be reduced if prior warning of incipient rollover were given to the operator by a rollover warning

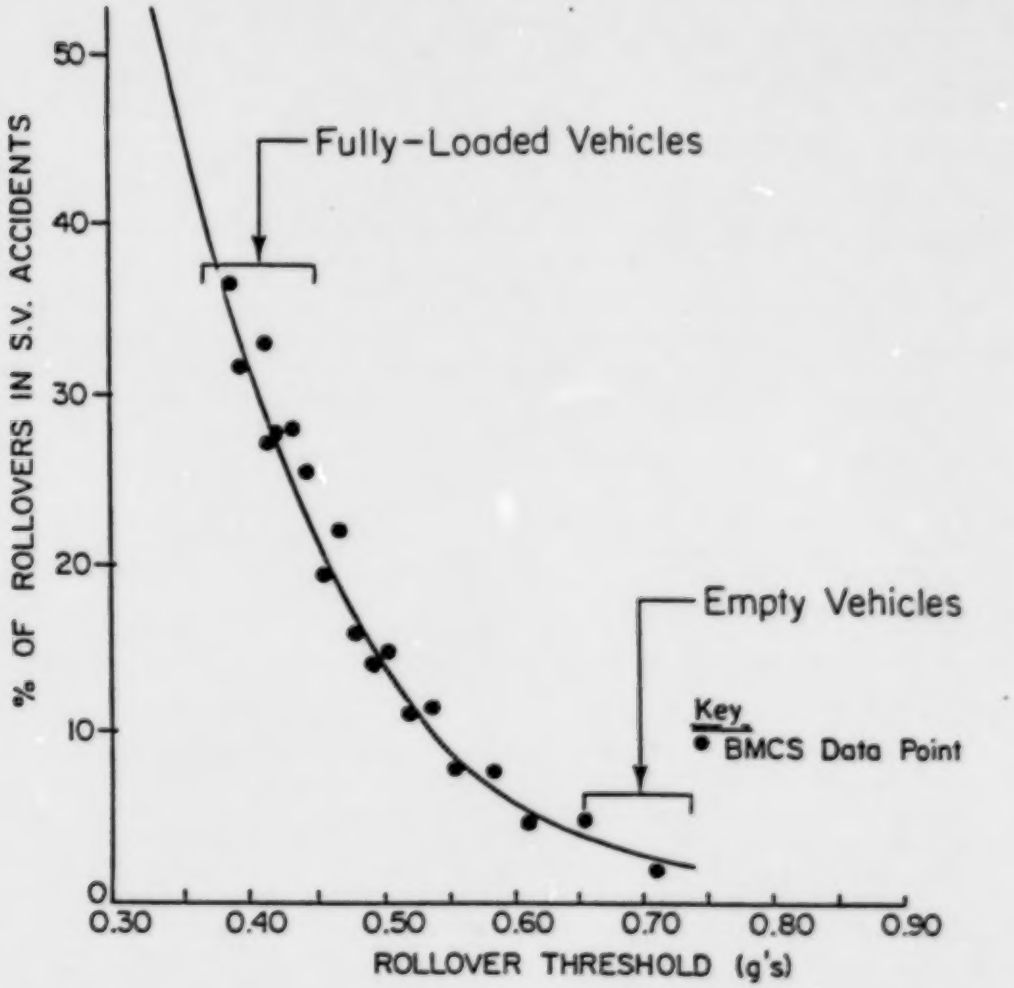

Figure 2 The percentage of rollovers in single-vehicle accidents vs. rollover threshold (from Ervin 1983).

device. With sufficient warning, the operator might be able to initiate a recovery.

It is important to note that not all vehicle rollovers can be considered recoverable. Those involving tripping over curbs or guard rails, those resulting from extreme manoeuvres, such as jackknifing, and those involving off-road excursions into ditches could not possibly be averted by the presence of a rollover warning device. However, rollovers that result from excessive speed on highway ramps and other corners and from the lateral accelerations encountered in rapid lane changing might well be recoverable with early recognition by the driver.

In many cases, the very large variations in payload and payload CG height that are common with heavy vehicles make it difficult for the operator to learn the vehicle's inherent roll performance. It is in these instances that a device to warn of impending rollover (and particularly of the rollover of the rear trailer in a double combination) could be an effective addition.

2.0 A SURVEY OF ROLLOVER ACCIDENTS INVOLVING HEAVY COMMERCIAL TRUCKS

As part of this project, a study was undertaken by Sparks and Berthelot (1989) to identify the cost-effectiveness of a rollover warning device (RWD). It examined a database of heavy truck accident records and attempted to identify the proportion of rollover accidents that could have been prevented by the existence of an RWD. While the complete text of the resulting report is available separately, this section reviews the study and summarizes its conclusions.

The study was based on documentation of 661 accidents involving tractor-semitrailers, A-trains, B-trains and C-trains from four different vehicle fleets operating throughout western Canada and the northwest U.S.A. The four vehicle types accounted for 44.6, 35.4, 15.1 and 4.8% of the accidents, respectively, recorded over a four-year period (1983 to 1986) in which the total mileage was approximately 500 million kilometres.

The report does not identify how many vehicles of each type existed in the four fleets or the distance travelled by each vehicle type. While the number of accidents suffered by each of the four types varies by nearly an order of magnitude, Sparks and Berthelot assume the differences are attributable only to the differences in the number of vehicles of each type in the four fleets. They then break down the 661 accidents into the following mutually exclusive categories:

- rollover
- hit the ditch
- (caused by a) third party
- jackknife
- hit animal
- driver error
- equipment malfunction

Table 1 shows the results by accident type. The table shows, for example, that 17.6% of all tractor-semitrailer accidents in the study were associated with vehicle rollover, and that the corresponding values for A-train, B-train and C-train accidents are 34.2%, 9.0% and 31.3%, respectively. Overall, 22.8% of the 661 accidents were classified as rollover accidents.

Table 1.
(from Sparks and Berthelot 1989)

Accident Distribution by Accident Type by Configuration

Carriers #1 to #4

1983 - 1986

Configuration	Rollover #	Rollover %	Hit Ditch #	Hit Ditch %	Third Party #	Third Party %	Jackknife #	Jackknife %	Hit Animal #	Hit Animal %	Driver Error #	Driver Error %	Equipment Malfunction #	Equipment Malfunction %	Total #	Total %
Semi-Trailer	52	17.63%	29	9.83%	134	45.42%	20	6.78%	46	15.59%	10	3.39%	4	1.36%	295	100.00%
A-Train	80	34.19%	18	7.69%	82	35.04%	19	8.12%	29	12.39%	5	2.14%	1	0.43%	234	100.00%
B-Train	9	9.00%	14	14.00%	39	39.00%	9	9.00%	23	23.00%	2	2.00%	4	4.00%	100	100.00%
C-Train	10	31.25%	5	15.63%	8	25.00%	3	9.38%	4	12.50%	2	6.25%	0	0.00%	32	100.00%
Total	151	22.84%	66	9.98%	263	39.79%	51	7.72%	102	15.43%	19	2.87%	9	1.36%	661	100.00

Sparks and Berthelot make a further breakdown of the 22.8% of the accidents involving rollover into these categories:

- preventable
- potentially-preventable
- non-preventable
- unknown

In this context, a rollover accident classified as "preventable" is one in which the vehicle operator would have been able to avoid rollover if an effective rollover warning device had been installed and operating at the time of the accident. This is a subjective assessment made by Sparks and Berthelot based on the description of the accident in the accident report. A "potentially-preventable" rollover is one that might have been prevented, depending on the performance of the warning device and the skill of the operator. Table 2 shows that only 3.3% of the total rollover accidents were judged "preventable," a further 38.4% were "potentially-preventable," and 49.7% were "non-preventable." The remaining 8.6% were classified as "unknown if preventable."

The report also identifies the accident cost (in monetary damages only), the number of injuries and the number of fatalities for each of the seven accident-type categories described. While rollover accidents accounted for only 22.8% of the total number of accidents (i.e., 151 + 661), they accounted for 61.8% of the total damages ($3.5 million + $5.7 million), 29% of the number of injuries (27 + 93) and 28.6% of the number of fatalities (10 + 35).

Table 2.
(from Sparks and Berthelot 1989)

Accident Distribution by Rollover Classification by Configuration

Carriers #1 to #4

1983 - 1986

Configuration	Rollover Accidents								Potential Rollover Accidents		* Other Accidents		Total Accidents	
	Preventable		Potentially Preventable		Non Preventable		Unknown		Total Rollovers		% of Total					
	#	%	#	%	#	%	#	%	#	%		#	%	#	%	#	%
Semi-Trailer	2	3.85%	16	34.62%	26	50.00%	6	11.54%	52	100.0%	17.63%	50	16.95%	193	65.42%	295	100.0%
A-Train	2	2.50%	34	42.50%	38	47.50%	6	7.50%	80	100.0%	34.19%	35	14.96%	119	50.85%	234	100.0%
B-Train	1	11.11%	3	33.33%	4	44.44%	1	11.11%	9	100.0%	9.00%	24	24.00%	67	67.00%	100	100.0%
C-Train	0	0.00%	3	30.00%	7	70.00%	0	0.00%	10	100.0%	31.25%	7	21.88%	15	46.88%	32	100.0%
Total	5	3.31%	58	38.41%	75	49.67%	13	8.61%	151	100.0%	22.84%	116	17.55%	394	59.61%	661	100.0%

* Other Accidents: Accidents that are not related to rollovers (e.g., Third Party, Hit Animal, some Driver Error, some Equipment Malfunction, some Jackknife).

A breakdown of the severity of the 22.8% of the accidents that involved rollover is given in Table 3. The severity is measured in monetary costs and in the numbers of injuries and fatalities. The table shows that the preventable rollovers account for only 3% of the total monetary costs of rollover accidents. The potentially-preventable and non-preventable rollover accidents account for 37.8% and 48.8%, respectively, while the unknown rollover accidents account for 10.4% of the costs. With respect to injuries and fatalities, the preventable rollovers account for 3.7% and 0%, respectively; the potentially-preventable account for 18.5% and 30%; the non-preventable account for 77.8% and 60%; and the unknowns account for 0% and 10%. It should be noted that some of the numbers involved here are small in an absolute sense. For example, in all of the 149 rollover accidents, there were only 27 injuries and 10 fatalities. Thus, care should be taken in extrapolating these results beyond the sample that they represent.

An interesting comparison can be made between the Sparks and Berthelot data and corresponding U.S. large truck (GVW > 10,000 lb) accident data recorded with the National Highway Traffic Safety Administration's Fatal Accident Reporting System. In a recent review, Seiff (1990) reported that the U.S. large truck fatality rate decreased from 5.80 fatalities per hundred million miles in 1976 to 4.16 in 1987. By comparison, the Sparks and Berthelot survey recorded 10 fatalities in 500 million kilometres, or 3.2 fatalities per hundred million miles. Vehicle rollover occurred in 60.3% of the fatal U.S. large truck accidents, whereas Sparks and Berthelot's corresponding figure was 90%.

Sparks and Berthelot estimated the cost-effectiveness of a rollover warning device by assuming it would eliminate only the preventable rollover accidents. Among the accidents surveyed, it could have been

Table 3
(from Sparks and Berthelot, 1989)

Rollover Severity by Rollover Classification

Carriers #1 to #4

1983 - 1986

Configuration	Preventable			Potentially Preventable			Not Preventable			Unknown if Preventable			Total Rollovers		
	Cost	# of Injur.	# of Fatal.	Cost	# of Injur.	# of Fatal.	Cost	# of Injur.	# of Fatal.	Cost	# of Injur.	# of Fatal.	Cost	# of Injur.	# of Fatal.
Semi-Trailer	$58,637	0	0	$455,905	3	0	$595,861	8	2	$227,552	0	1	$1,337,935	11	3
% of Total	4.38%	0.00%	0.00%	34.08%	27.27%	0.00%	44.53%	72.73%	66.67%	17.01%	0.00%	33.33%	100.00%	100.00%	100.00%
A-Train	$24,521	0	0	$599,782	1	3	$776,757	9	3	$137,690	0	0	$1,538,750	10	6
% of Total	1.59%	0.00%	0.00%	38.98%	10.00%	50.00%	50.48%	90.00%	50.00%	8.95%	0.00%	0.00%	100.00%	100.00%	100.00%
B-Train	$22,911	1	0	$170,178	0	0	$97,820	1	0	$1,814	0	0	$292,723	2	0
% of Total	7.83%	50.00%	0.00%	58.14%	0.00%	0.00%	33.42%	50.00%	0.00%	0.62%	0.00%	0.00%	100.00%	100.00%	100.00%
C-Train	$0	0	0	$106,955	1	0	$250,123	3	1	$0	0	0	$357,078	4	1
% of Total	0.00%	0.00%	0.00%	29.95%	25.00%	0.00%	70.05%	75.00%	100.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%
Total	$106,069	1	0	$1,332,820	5	3	$1,720,561	21	6	$367,056	0	1	$3,526,486	27	10
% of Total	3.01%	3.70%	0.00%	37.79%	18.52%	30.00%	48.79%	77.78%	60.00%	10.41%	0.00%	10.00%	100.00%	100.00%	100.00%

expected to eliminate just one injury (3.7% of the total) and $106,069 in damages (3% of the total). The average damage per vehicle per year due to preventable rollover accidents was estimated at $42.43. From this, they determined that at the time of purchase (of a new truck), an operator could afford to invest only $152.95 on a rollover warning device if the decision were based on economic probability alone.

In practice, it might be expected that a rollover warning device would also eliminate some of the potentially-preventable accidents, and that this would have a significant effect on the amount an operator could afford to invest. For example, if a rollover warning device also eliminated 25% of the potentially-preventable accidents, then the economically-justifiable amount an operator would invest increases from $153 to $633. In addition, a proportion of the injuries and fatalities associated with the potentially-preventable accidents would also be eliminated. For the group of 149 rollover accidents examined, the 27 injuries and 10 fatalities would then drop to 25 injuries and 9 fatalities. The effect on the overall total of 661 accidents would be a reduction from 93 injuries to 91 and from 35 fatalities to 34.

It should also be noted that there are additional advantages to reducing the number of rollover accidents not included in the dollar values quoted above. These advantages include reductions in potential environmental damage, public health care costs and claims for disability pensions and workers' compensation.

3.0 THE MECHANICS OF ROLLOVER

As indicated in Section 1, rollover can result from a large number of causes, not all of which are potentially preventable by a rollover warning device (RWD). Tripping accidents (where the vehicle slides sideways into a physical barrier, such as a curb, and then trips over it), rollover following jackknifing and off-road excursions into ditches are all rollover accident cases in which an RWD would not be capable of providing any useful warning to the driver. Instances where a warning would be useful include excessive speed on highway ramps and corners and for rapid lane changes. This section reviews the mechanics of rollover for this latter accident group, with the intention of identifying a potential technique for detecting incipient rollover.

The process of rollover normally results from a lateral acceleration level sufficient to tip the vehicle over. Some road surfaces (highway ramps, for example) are not horizontal, but are banked or superelevated. When a vehicle negotiates a corner, the most significant external factor affecting rollover is the ratio of the forces applied to the tires in the direction parallel to the road surface, to the forces applied in the direction normal to the surface. Because both these forces arise from accelerations (centrifugal and gravitational, respectively), the force ratio is identical to the corresponding acceleration ratio. On a laterally sloped surface, the accelerations in both of these directions are derived from components of the lateral acceleration (parallel to the earth's surface) and the gravitational acceleration acting on the vehicle's centre of gravity. While vehicle speed, road radius of curvature and road surface slope have a significant effect on the magnitudes of the two accelerations, they do not significantly alter the maximum value of the acceleration ratio that a vehicle can sustain without rolling over. Thus, for simplicity, the following discussions assume the vehicle is operating on a horizontal road surface. This means the acceleration parallel to the road surface is due solely to the lateral acceleration from cornering, and the acceleration normal to the road surface is due solely to gravitation.

3.1 A Single-Axle Model

To examine the roll response of a commercial vehicle, it is useful to consider the simple single-axle vehicle model shown in Figure 3 operating under quasi-steady-state conditions. This model can describe the roll response of a single-axle vehicle that is not roll-coupled to other axles on the vehicle (e.g., a single-axle trailer with a pintle hook). A single-axle model is normally inadequate for describing the roll response of a multi-axle vehicle because it disregards the axle-to-axle differences that may exist in such parameters as tire characteristics, loads and roll stiffnesses, as well as the roll-coupling parameters (frame torsional stiffness, fifth-wheel roll stiffness, etc.). Nevertheless, it can form a basis for more complex multi-axle models that do account for these factors.

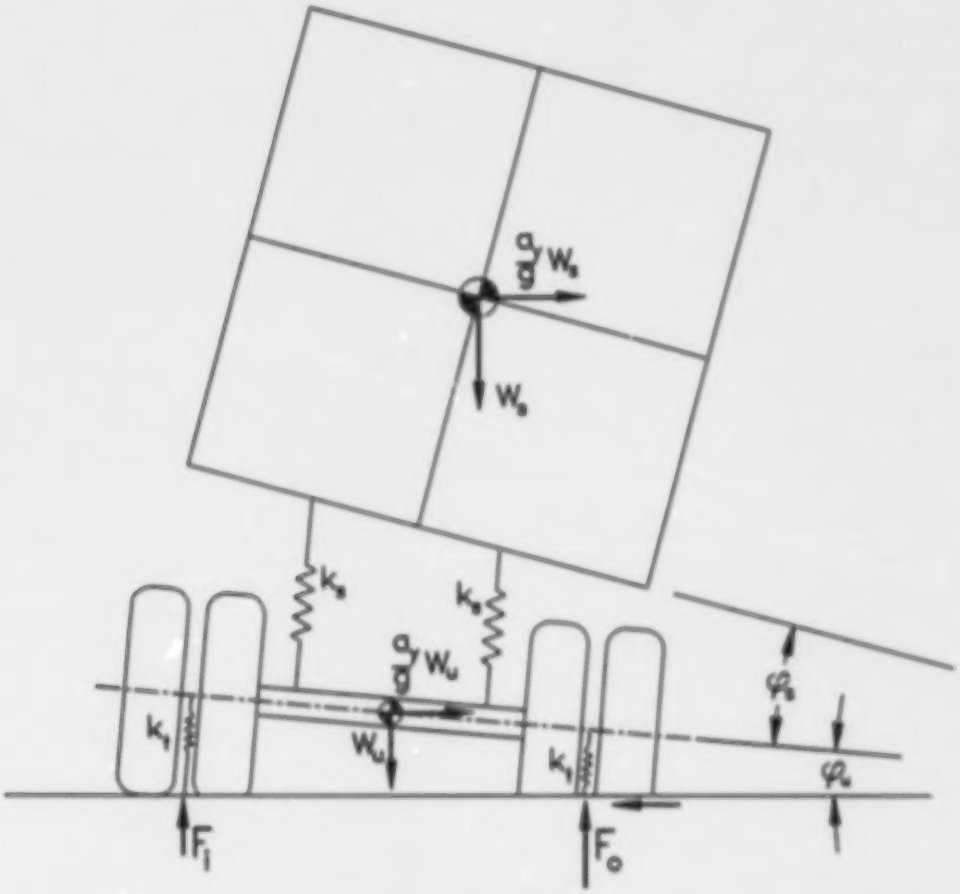

Figure 3 A single-axle roll model showing axle and body roll with suspension springs.

The single-axle representation shown in the figure is not as complete as some of the existing models (e.g., Mallikarjunarao 1982) in that it neglects such features as lateral tire stiffness (and the associated overturning moment), non-linear suspension characteristics (including hysteresis and spring "lash") and off-centre CG location. Nevertheless, the model in Figure 3 is sufficient to describe the fundamental roll response of most heavy vehicles.

This model is used to demonstrate the relationship between the lateral acceleration applied to the vehicle and its roll response. The roll characteristics of the single-axle model are described with the aid of a "roll response diagram." This diagram then forms the basis of a description, in Section 3.2, of the roll response of a multi-axle vehicle.

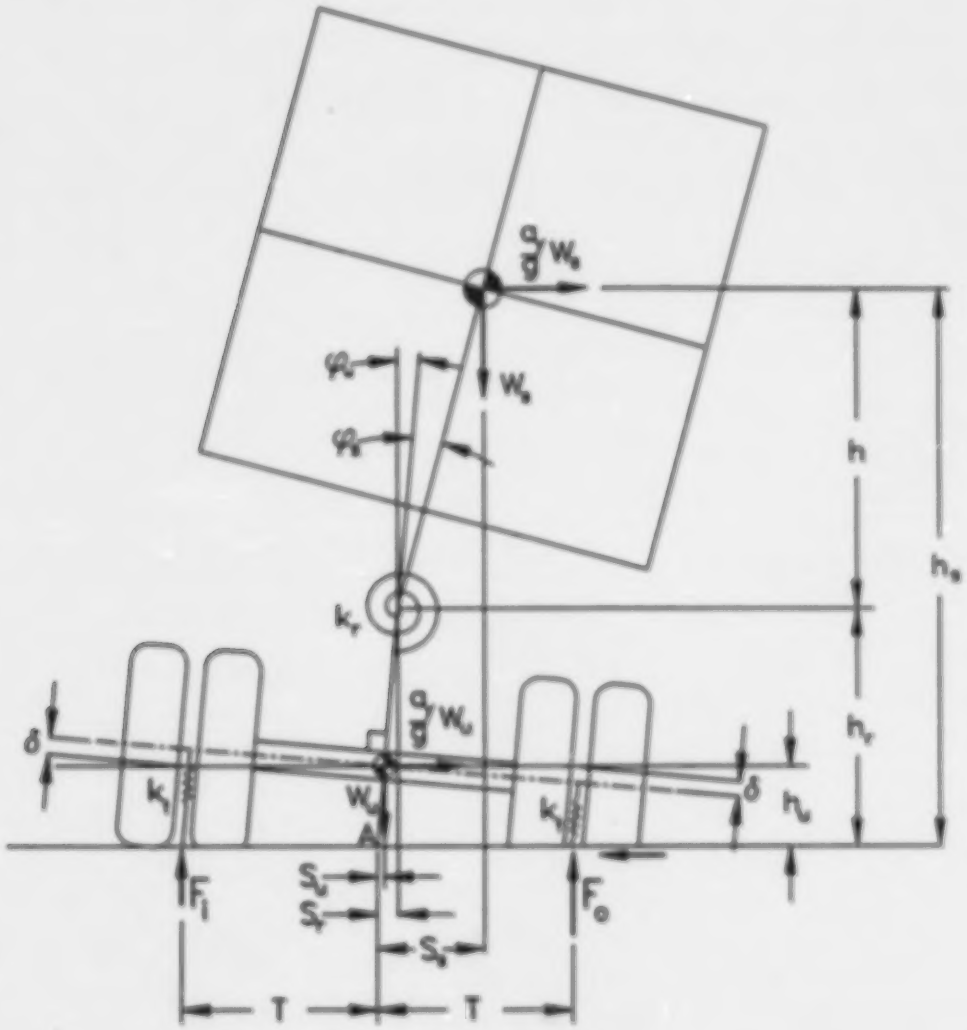

Figure 4 A single-axle roll model with the body rotating about a roll centre.

3.1.1 The Relationship Between Lateral Acceleration and Roll Angle

Almost all commercial vehicle suspensions combine rigid axles with suspension elements, usually leaf springs or air springs, but occasionally rubber blocks or torsion bars. Regardless of the suspension type, the lateral acceleration a_y encountered during cornering will cause the vehicle to roll outward, as shown in Figure 3. The axle rolls through an angle φ_v relative to the road surface (due to changes in the rolling radii of the tires), and the body rolls through an additional angle φ_s relative to the axle as a result of the

compression and elongation of the outboard and inboard suspension springs. The two springs provide a resisting roll stiffness k (i.e., the resisting moment per unit of roll angle) that, as a first-order approximation, can be described as a function of the individual spring stiffnesses k_s and the lateral spring spacing T_s:

$$k = 2k_s\left(\frac{T_s}{2}\right)^2. \tag{1}$$

Other mechanisms, such as separate anti-roll bars or the longitudinal twisting of leaf springs, may result in an auxiliary roll stiffness k_{aux}. The composite roll stiffness k_r for the axle is the sum of the spring roll stiffness k and the auxiliary roll stiffness k_{aux}:

$$k_r = 2k_s\left(\frac{T_s}{2}\right)^2 + k_{aux}. \tag{2}$$

When the vehicle body rolls, it rotates about a point known as the roll centre. The height of the roll centre on an actual vehicle largely depends on the characteristics of the suspension. For a simple leaf spring suspension, the roll centre is normally located on the vehicle centreline at the same height as the springs. In practice, it has been found (Fancher et al. 1986) that the roll centre heights of heavy commercial tractors and trailers vary from approximately 450 to 800 mm (18 to 31 in.).

Figure 4 shows the single-axle vehicle model with a composite roll stiffness k_r acting at a roll centre height h_r above the road surface. In this figure, it is assumed the lateral locations of the two resultant forces F_o and F_i applied to the bottoms of the tires remain constant, regardless of the axle roll angle φ_u.

When the vehicle negotiates a turn, the lateral acceleration causes the axle to roll to an angle φ_u. This results in a lateral offset S_u between the unsprung mass centre of gravity (CG) and point A midway between the two forces F_i and F_o. Similarly, the roll centre is offset by a distance of S_r, and the sprung mass CG by a distance of S_s from the same midpoint. The distances S_u, S_r and S_s can be defined as follows (assuming the angles φ_u and φ_s are small):

$$S_u = h_u\tan(\varphi_u) \approx h_u\varphi_u \tag{3}$$

$$S_r = h_r\tan(\varphi_u) \approx h_r\varphi_u \tag{4}$$

$$S_s = h_s\tan(\varphi_u) + h\tan(\varphi_s + \varphi_u) \approx h\varphi_s + h_s\varphi_u \ . \tag{5}$$

The lateral acceleration a_y results in the lateral forces $W_s a_y/g$ and $W_u a_y/g$ acting at the sprung mass and unsprung mass CGs, respectively, where g is the gravitational constant and W_s and W_u are the weights of the sprung and unsprung masses.

The sprung mass roll angle φ_s can be determined by taking moments about the roll centre:

$$\sum M_{\text{roll centre}} = 0 = -k_r\varphi_s + W_s(S_s - S_r) + hW_s\frac{a_y}{g}$$

$$0 = -k_r\varphi_s + W_s(h\varphi_s + h\varphi_u + h\frac{a_y}{g})$$

$$\varphi_s(k_r - hW_s) = W_s h(\varphi_u + \frac{a_y}{g})$$

$$\varphi_s = \frac{W_s h(\varphi_u + \frac{a_y}{g})}{k_r - W_s h} = \frac{\varphi_u + \frac{a_y}{g}}{\frac{k_r}{W_s h} - 1} \quad . \tag{6}$$

The forces F_i and F_o can be defined in terms of the vertical dual tire stiffnesses k_t, the tire deflection δ_0 when $\varphi_u = 0$, and the change in deflection δ that occurs when φ_u becomes non-zero. In turn, the deflection change δ is geometrically related to the axle roll angle φ_u:

$$F_i = k_t(\delta_0 - \delta) \tag{7}$$

$$F_o = k_t(\delta_0 + \delta) \tag{8}$$

$$\delta = T\varphi_u \quad . \tag{9}$$

By taking moments about point A on the ground midway between F_i and F_o, a second relationship between the roll angles φ_u and φ_s can be established:

$$\sum M_A = 0 = (F_i - F_o)T + W_u S_u + W_u\frac{a_y}{g}h_u + W_s S_s + W_s\frac{a_y}{g}h_s \quad . \tag{10}$$

Substituting Equations 3, 4, 5, 7, 8 and 9 into Equation 10 gives the following:

$$0 = -2k_t T^2\varphi_u + W_u h_u\varphi_u + W_u h_u\frac{a_y}{g} + W_s h\varphi_s + W_s h_s\varphi_u + W_s h_s\frac{a_y}{g}$$

$$\varphi_u(2k_t T^2 - W_u h_u - W_s h_s) = W_s h\varphi_s + \frac{a_y}{g}(W_u h_u + W_s h_s) \quad . \tag{11}$$

A further substitution of Equation 6 into 11 results in an explicit expression for φ_u:

$$\varphi_u(2k_tT^2-W_uh_u-W_sh_s)-\frac{a_y}{g}(W_uh_u+W_sh_s) = \frac{W_sh(\varphi_u+\frac{a_y}{g})}{\frac{k_r}{W_sh}-1}$$

$$\varphi_u = \frac{\frac{a_y}{g}\left[(W_uh_u+W_sh_s)(\frac{k_r}{W_sh}-1)+W_sh\right]}{(2k_tT^2-W_uh_u-W_sh_s)(\frac{k_r}{W_sh}-1)-W_sh} \quad . \tag{12}$$

From this it can be concluded that the unsprung mass roll angle φ_u is proportional to the lateral acceleration a_y. In conjunction with Equation 6, it reveals that the sprung mass roll angle φ_s is proportional to a_y.

3.1.2 The Lateral Load Transfer Ratio

Intuitively, it can be seen that the progression towards rollover is closely associated with the lateral transfer of vertical load from the tires on the inside of the turn to those on the outside. The single-axle model in Figure 4 will actually become unstable and will roll over when the inside tire load F_i reaches zero and the outside load F_o reaches W_u+W_s. A useful parameter for characterizing this load transfer is the lateral load transfer ratio (LTR), defined as follows (Ervin and Guy 1986):

$$\text{LTR} = \frac{F_o-F_i}{F_o+F_i} \quad . \tag{13}$$

This can be rewritten using Equations 7, 8 and 9 and by observing that the total tire load F_o+F_i is equal to W_s+W_u:

$$\text{LTR} = \frac{2k_t\varphi_u}{W_s+W_u} \quad . \tag{14}$$

Since it has been established the roll angle φ_u is proportional to the lateral acceleration a_y, it is clear the LTR is also proportional to a_y. The value of the LTR will vary from zero when the lateral acceleration is zero and the loads carried by the tires are equal, to 1.0 when the lateral acceleration reaches the point where the load F_i drops to zero. If the lateral acceleration increases beyond the level at which the LTR equals 1, the vehicle becomes unstable and rolls over. Between these values, the LTR provides a continuous indication of the relative lateral

acceleration of the vehicle. For example, a single-axle vehicle that experiences an LTR of 0.6 when negotiating a curve is subjected to approximately 60% of the lateral acceleration that is required to roll it over.

The LTR is a useful non-dimensional parameter for indicating how close a vehicle is to rolling over. It can provide a standard basis for comparison of the rollover potential of different vehicles, irrespective of vehicle design parameters or loading conditions. Calculation of the LTR using Equation 13 is independent of parameters that are normally difficult to measure, such as the CG height, roll centre height and axle and body roll angles. These characteristics make the LTR particularly attractive for the purpose of rollover prediction.

3.1.3 The Roll Response Diagram

The roll behaviour of the single-axle vehicle model can be visualized with the aid of a roll response diagram (Mallikarjunarao 1982). In this diagram, the overturning moments and roll-resisting moments are plotted against the body roll angle. These moments are taken from the moment balance equation

$$M_o = M_r - M_s \tag{15}$$

where:

M_o is the primary overturning moment, i.e., the moment about a point on the road surface resulting from the lateral acceleration of the mass centres;

M_r is the roll-resisting moment, i.e., the moment about a point on the road surface halfway between the tires resulting from the roll-resisting forces applied by the road surface to the tires on the axle; and

M_s is the secondary overturning moment, i.e., the moment about a point on the road surface halfway between the tires resulting from the roll-induced lateral shift of the CG.

The basic features of a roll response diagram for the single-axle model are shown in Figure 5. The right side of the diagram plots roll moment against body roll angle, while the left side plots roll moment against lateral acceleration. The roll-resisting moment of the axle is shown to increase linearly with roll angle from the origin to point A. At this point, all of the load has been transferred to the tires on one side of the vehicle; thus, a further increase in roll angle simply results in wheel lift-off and no further increase in the roll-resisting moment.

The secondary overturning moment is shown below the horizontal axis in Figure 5 to facilitate the subtraction identified in Equation 15. Unlike the roll-resisting moment, this moment continues to increase with roll angle beyond the point at which wheel lift-off occurs.

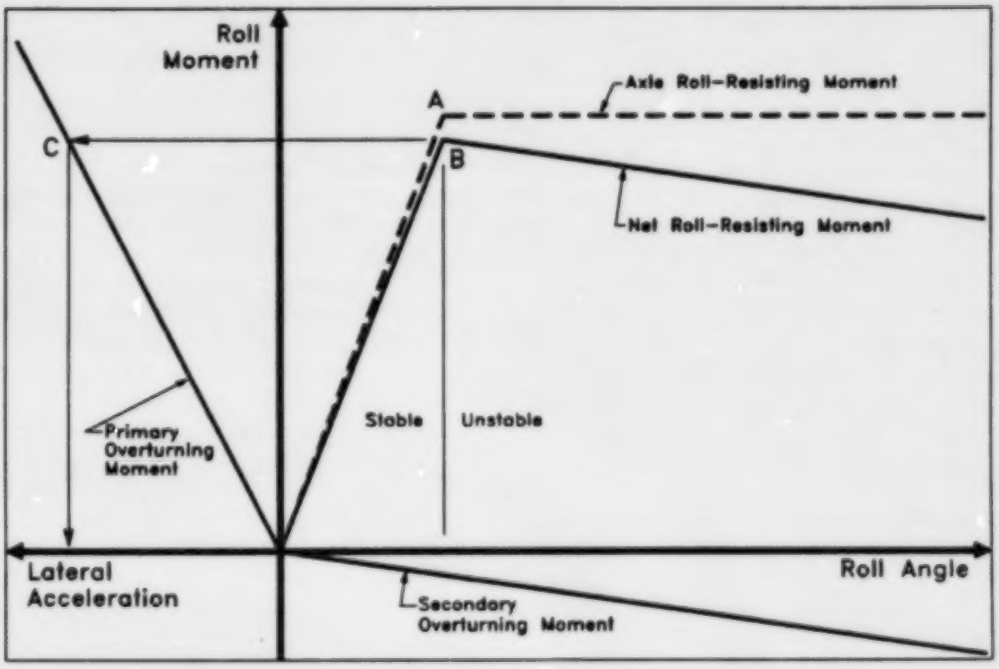

Figure 5 A roll-response diagram for a single-axle vehicle.

The difference between the roll-resisting moment and the secondary overturning moment is referred to as the net roll-resisting moment. The net roll-resisting moment rises linearly to a maximum at B, and then decreases gradually with further increase in roll angle, as shown in the figure.

The left side of the figure shows that the primary overturning moment increases continuously with lateral acceleration. As indicated by Equation 15, the primary overturning moment equals the net roll-resisting moment. Thus, the maximum primary overturning moment that can be applied is readily identified by drawing a horizontal line from the maximum net roll-resisting moment, at point B, to point C on the primary overturning moment curve. The corresponding maximum lateral acceleration can then be found by following a vertical line from C down to the Lateral Acceleration axis. This acceleration, referred to as the rollover threshold, is normally expressed in units of gravitational acceleration.

An important feature of the roll response diagram is that the slope of the net roll-resisting moment curve provides an indication of the relative roll stiffness of the vehicle. In the case shown in Figure 5, the roll stiffness is constant up to the roll angle at which wheel lift-off occurs. Further increase in the roll angle beyond this point

results in a decrease in the net roll-resisting moment, thus indicating the vehicle becomes unstable beyond B and essentially tips over.

3.2 A Rigid-Body Multi-Axle Model

The single-axle model described in the Section 3.1 is normally inadequate for describing the roll response of a real vehicle because it does not account for axle-to-axle variations in load, roll stiffness and other related parameters. In addition, it neither considers the effects of coupling devices such as trailer hitches or fifth wheels, nor the torsional stiffness of the frame between one axle and the next. While models that consider all of these effects do exist, their description is beyond the current scope. This section briefly reviews the effects of axle-to-axle variations in such parameters as load and roll stiffness. For this purpose, it is assumed that the vehicle is torsionally rigid, which implies that the body roll angle remains constant along the length of the vehicle.

A roll response diagram similar to that used for the single-axle model can be used to examine qualitatively the roll response of a rigid-body multi-axle vehicle. In extending the diagram to a multi-axle vehicle, the moment equation shown previously as Equation 15 becomes

$$\sum M_a - \sum M_r - \sum M_s \qquad (16)$$

where the summations are made over all of the axles on the vehicle. The roll response diagram for a hypothetical multi-axle tractor-semitrailer is shown in Figure 6, where the roll-resisting moments of the tractor front axle, the tractor tandem axle group and the trailer tandem-axle group are given individually. Because it is assumed the roll angle remains constant along the length of the vehicle, a single line can be used to represent the secondary overturning moment of the entire vehicle.

The net roll-resisting moment shown in the diagram is obtained by adding the three roll-resisting moments, then subtracting the secondary overturning moment. It can be seen that each of the additional axles in this model results in an additional inflection point in the net roll-resisting moment curve. The first change in slope occurs at A, where trailer axle wheel lift-off occurs. Despite the trailer wheel lift-off, further increase in the roll angle results in a continuing increase in the net roll-resisting moment (albeit at a reduced rate). At B, lift-off of the tires on one side of the tractor tandem-axle group occurs, resulting in a further change in the slope of the net roll-resisting moment curve. However, this time the slope becomes negative,[1] indicating the roll response of the vehicle has become

[1] The slope becomes negative because the secondary overturning moment grows more rapidly (with roll angle) than the roll-resisting moment of the tractor front axle.

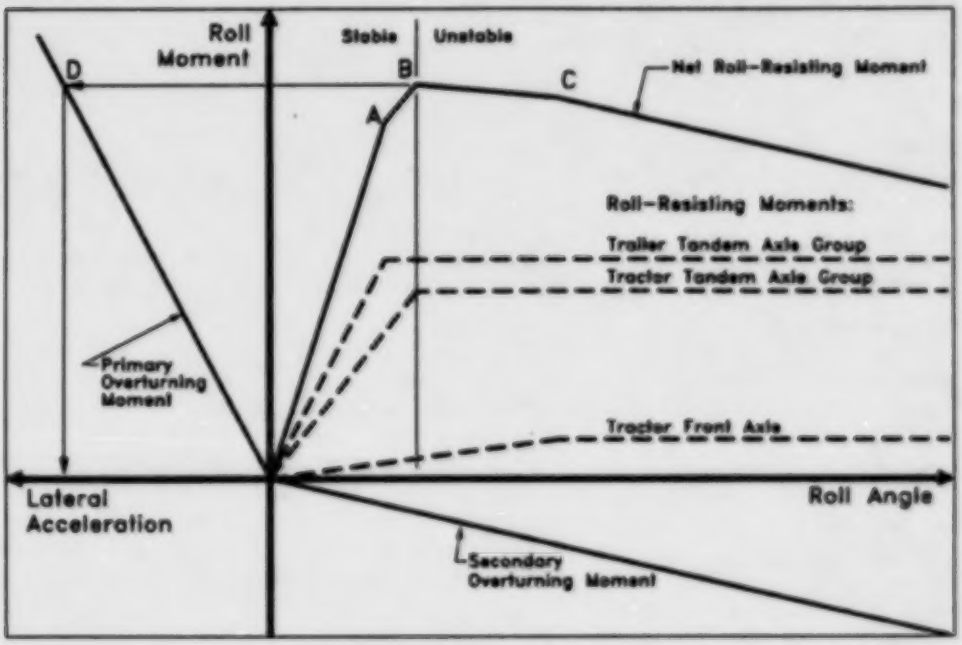

Figure 6 A roll-response diagram for a tractor-semitrailer.

unstable. As the roll angle increases in this unstable region, front axle wheel lift-off occurs at C. At this point, all of the tires on one side of the vehicle are off the ground, and roll-over is essentially assured.

The roll response in Figure 6 shows that the maximum net roll-resisting moment occurs at B. Thus, the vehicle rollover threshold is the lateral acceleration at which the primary overturning moment (point D) equals the net roll-resisting moment at B. In the example shown, it is interesting to note this rollover threshold does not occur at first wheel lift-off (i.e., at A), or at the point where all of the wheels on one side of the vehicle have lifted off (C). The particular order in which wheel lift-off occurs depends entirely on vehicle design parameters and loading conditions. Nevertheless, most heavy commercial vehicles are designed with very low front suspension roll stiffness so that the front wheel is always the last to lift off in a rollover.

If individual lateral load transfer ratios were calculated for each axle on the vehicle represented in Figure 6, the LTR for the trailer tandem-axle group would become 1 at point A, the LTR for the tractor tandem-axle group would become 1 at B and the LTR for the tractor front axle would become 1 at C. An overall load transfer ratio $LTR_{vehicle}$ can be calculated for the vehicle, as shown in the following equation, where the summation is made over all of the axles on the vehicle.

$$LTR_{vehicle} = \sum \frac{(F_o - F_i)}{(F_o + F_i)} \quad . \qquad (17)$$

In this case, $LTR_{vehicle}$ begins with a value of zero when the lateral acceleration is zero, but does not reach 1 until complete wheel liftoff is achieved at C. This means the roll of the vehicle becomes unstable at point B when $LTR_{vehicle}$ is greater than zero but less than 1. The specific value at which the instability (and hence the rollover) is initiated will depend on vehicle design parameters and loading conditions.

In the LTR definition proposed by Ervin and Guy (1986), it was suggested an individual LTR value be calculated for each vehicle unit, where a vehicle unit is a group of roll-coupled elements. In the case of an A-train, for example, the tractor and semitrailer are considered to be a single vehicle unit because they are roll-coupled by the fifth wheel, while the full trailer constitutes a second vehicle unit. Fancher et al. also suggested the LTR value for the tractor should not include the front axle since its roll stiffness is proportionately much less than that of other axles, and thus its effect on the roll response of the vehicle is minimal. Even with these definitions, however, unstable rollover will not necessarily be initiated only when the LTR value equals 1. Nevertheless, these definitions are probably capable of providing LTR values for existing heavy vehicles that are consistently close to 1 when rollover is initiated.

4.0 DESIGN CONSIDERATIONS AND THE EXPECTED PERFORMANCE OF A ROLLOVER WARNING DEVICE

In evaluating the feasibility of a rollover warning device (RWD), it is important to outline the basic functional requirements of the device. These are identified in Section 4.1. As described in Section 3, the lateral load transfer ratio (LTR) is a suitable parameter for detecting incipient rollover; thus, Section 4.2 outlines some possible techniques for measuring this value. Section 4.3 details some of the more important design features that should be considered for an LTR-based rollover warning device. As described in this section, measurement of the LTR is a relatively involved procedure requiring a number of load cells that are installed between the vehicle suspension and body; thus, Section 4.4 examines the potential of a different technique, lateral acceleration measurement, as a basis for predicting rollover.

4.1 THE BASIC FUNCTIONAL REQUIREMENTS OF A ROLLOVER WARNING DEVICE

A list of characteristics the authors consider desirable for a rollover warning device is contained in Table 4. Although not all are deemed essential, it is anticipated that a RWD that is useful and acceptable in the intended market will require most of them.

4.2 LATERAL LOAD TRANSFER MEASUREMENT

As indicated in Section 3, vehicle rollover is closely associated with the lateral transfer of load. This close relationship makes it apparent that the proximity of the vehicle to rolling over can be monitored by measuring lateral load transfer. As described in Section 3.1.2, Ervin and Guy (1986) introduced a measure called the lateral load transfer ratio (LTR), which can be obtained from the measurement of individual wheel loads. The LTR will be approximately equal to zero when the vehicle unit is at rest on a level surface and will rise to a value close to 1 when all of the tires on one side of the unit (with the exception of the tire on the steering axle) lift off. Between these limits, the LTR provides a relatively continuous, normalized indication of how close the vehicle is to rollover.

Among the desirable RWD characteristics shown in Table 4, items 9 and 10 are certainly two of the most important. In heavy vehicle operation, the payload always forms a very high proportion of the gross vehicle weight. This means that changes in payload characteristics (such as payload CG height or longitudinal position) can result in large changes in vehicle handling and rollover performance. The resulting wide performance range makes it difficult for the driver to operate the vehicle with a consistent margin of safety, the maintenance of which is one of the major objectives of the RWD. LTR is a proxy for rollover that is relatively independent of the payload weight and CG height; thus, RWDs that use it would satisfy items 9 and 10 in the table.

Appropriate criteria must be selected for the purpose of providing a warning of incipient rollover. A straightforward criterion might be when the LTR for the vehicle exceeds a predetermined value such as 0.6. Alternatively, individual load transfer ratios could be calculated for one or more axles on the vehicle, then a warning could be given when they exceeded some combination of predetermined values. Perhaps, for example, one axle LTR value would have to exceed 0.7 and all of the remaining axle LTR values would have to exceed 0.5. More complex criteria might involve a time-based averaging of these values to reduce the noise effects that can be expected when the vehicle is operating on rough road surfaces. The selection of final LTR-based rollover warning criteria would have to be the result of further investigation and vehicle tests.

A question arises regarding the number of axles that need to be monitored. Is it necessary to monitor the lateral load transfer on all of the axles on the vehicle, or is it sufficient to monitor the load transfer on only the rear-most axle? To a significant extent, this will depend on the incremental cost of monitoring the load transfer on each axle and on the benefits of monitoring additional axles. While the prediction of rollover almost certainly would be better if all axles were monitored, a warning based only on measurements made at the rear-most axle might be sufficient for most vehicles and loading configurations.

Table 4
Characteristics of an ideal rollover warning device.

General:		
1)	Inexpensive.	The financial outlay for an RWD is a pure expense because the device generates no tangible payback. Low cost is thus important.
2)	Reliable.	Extended trouble-free service is important to truck owners. Where the mean vehicle miles travelled between failures is too low, the hardware will not sell. (When first introduced in the 1970s, a high failure rate resulted in widespread rejection and subsequently a repeal of the regulation that encouraged their introduction.)
3)	Suitable for installation on all types of vehicles.	Ideally, minimal design changes should be required for installation on all types of straight trucks, tractor-semitrailers and combination vehicles.
4)	Trailer-mounted components removable for trailer drop-off.	Where components of the RWD must be mounted on a trailer, they should be readily removable by the operator. If they are not, RWDs will be unsuitable for operators who pick up trailers at one location and drop them off at another.
Installation and Durability:		
5)	Require minimal installation effort.	Minimal installation effort will help both to reduce buyer resistance among fleet owners and private operators and to reduce future maintenance costs.
6)	No separate cables between vehicle units.	If sensors are used on a semitrailer, they should need no separate electrical cable connection to the tractor cab. This can be accomplished by using short-range telemetry or by adding a modulated signal to an existing power line.
7)	Environmental protection.	Transducers, cables and connectors must withstand water, salt and impact from foreign objects, and all components must withstand temperature extremes.

Table 4 (cont'd)
Characteristics of an ideal rollover warning device.

Installation and Durability (cont'd):

8) No field calibration required.	Ideally, no calibration should be required after installation. If calibration is required, the equipment to do it should be limited to what is readily available to all operators (e.g., weigh scales).

Performance:

9) Warning is independent of payload and of CG location and height.	The RWD must provide a consistent warning of incipient rollover for any combination of payload and CG location and height. Without this, an RWD will provide inaccurate predictions of rollover.
10) Consistent safety margin between warning and rollover.	The warning provided by the device should give the operator a warning that provides a consistent margin of safety prior to rollover. This safety margin should allow the operator sufficient time to respond with corrective action to avert the potential rollover.
11) Unaffected by installation on vehicles with high or low axle roll stiffnesses or torsionally soft or stiff frames.	The safety margin referred to should not be affected significantly by normal variations in the design characteristics of heavy vehicles.
12) Unaffected by road irregularities.	The warning given by the RWD should not be affected by varying levels of road roughness (small bumps, potholes, etc.) that are normally encountered.
13) Unaffected by conditions encountered during low-speed manoeuvring.	Often during low-speed manoeuvring, it is possible to have highly non-uniform tire load distributions, e.g., due to changes in road elevation, which may exist for extended periods of time. These should not result in warnings of impending rollover.

Table 4 (cont'd)
Characteristics of an ideal rollover warning device.

Features:

14) Warning of device failure.	The system should perform a self-test each time it is turned on, and it should notify the operator if it is non-functional.
15) Adjustable audio and visual warnings.	The most informative type of operator interface might include an analog scale (with green, yellow and red operating regions) showing the load transfer ratio or some similar measure. The device would also incorporate an audible warning of adjustable volume that would begin sounding a series of beeps when the analog scale was in the yellow region. The beeps could then become louder and faster as the reading on the analog scale increased.

The calculation of an axle's LTR value requires that the left- and right-side tire loads be measured. An overall LTR value for the vehicle can then be determined by averaging the axle LTR values. No simple methods exist for measuring the actual tire loading on the pavement when the vehicle is in motion. However, these tire loads can be estimated from load measurements made elsewhere on the vehicle. For example, wheel force transducers have been developed that sandwich between the wheel hub and the wheel to measure wheel loads when a vehicle is in motion. While they provide a very good estimate of tire loading (particularly when combined with vertical wheel acceleration data), they are extremely expensive and have limited durability.

Rather than measuring the wheel loads at the hubs, it is possible to measure loads either within or close to the suspension springs. Commercial on-board weigh scale systems have been developed in the past using various types of force transducers that mount on the frame rails of the truck or trailer (Philips 1989). While the forces measured at this location would not provide a highly accurate estimate of the actual LTR, it is probable they would be sufficient for the intended purpose.

Among the various transducer types that have been developed for on-board weigh scales, Philips (1989) reported that the best accuracy and durability was obtained with electronic load cells in the form of flat metal bars that are welded or bolted between the frame and a load-bearing portion of the vehicle. A second approach to measuring load transfer close to the springs involves inserting a device with a small strain-gauged sensing disk into a hole machined in a vertical portion of the frame above the suspension (Barnett and West 1983).

Lateral load transfer causes a change in frame stresses, which deforms the disk and provides an electrical output. A third approach uses pneumatic or hydraulic suspension of the payload combined with measurement of the associated pressure. This generally has not been a very satisfactory approach due to reliability problems. A special case for consideration is that of vehicles that make use of air suspension on each axle. While it is relatively simple to estimate the total vehicle payload from the pneumatic pressure, the existence of auxiliary roll stiffness devices (anti-roll bars, etc.) makes it impractical to determine the lateral load transfer simply by taking the difference between the pressures in the air springs on the left and right sides of an axle.

Load cell accuracy requirements for existing on-board weigh scale systems are high because of legal metrology stipulations. Philips (1989) reported that the standard error of the total vehicle weight measured by strain gauge load cells was approximately 2%. This level of accuracy is almost certainly higher than would be necessary for an effective rollover warning device based on the load transfer ratio.

The placement of the transducers close to the vehicle suspension means that little or none of the vehicle's unsprung weight would be included in the transducer output. To a certain extent, this could be overcome by having the display unit add an appropriate portion of the unsprung weight to the signal from each transducer before calculating the LTR. However, a technique would have to be established to determine the appropriate unsprung weight to be added. Possible techniques include the use of a fixed value, or of a value that could be set when the device is installed. The use of a predefined value means the lateral load transfer of the actual unsprung weight is not considered. However, the resulting error would be greatest when the vehicle is in the unloaded condition, where the risk of rollover is usually the least, and would diminish steadily as the payload is increased.

4.3 SPECIFIC DESIGN FEATURES OF A ROLLOVER WARNING DEVICE BASED ON THE LOAD TRANSFER RATIO

To satisfy most of the rollover warning device characteristics identified in Table 4, using the measurement of LTR as a basis for detecting incipient rollover, it is expected that the RWD would combine a cab-mounted display and signal processor with load cells mounted at one or more points on the vehicle.

This arrangement would be similar to that used for existing commercial on-board weigh scale systems. Both systems require the use of load cells and a cab-mounted display, with cabling between them. Hence, much of the experience gained with the development of weigh scale systems that have been on the market for a number of years is readily applicable to RWDs.

On-board weigh scale systems typically comprise load cells mounted at each side of the trailer axle and at the fifth wheel. While pneumatic and hydraulic load transducers have been used in the past for this application, as mentioned earlier, they have generally been found to be unsatisfactory, mainly because of high maintenance costs (Philips 1989). The most successful systems have used electronic load cells with various types of mechanical overload protection.

Where the rollover warning device is installed on an articulated vehicle, the rear-most axle on the vehicle is the most important to monitor because it is the axle most affected by rearward amplification and least affected by the tractor's stabilizing action. Thus, even the most basic installation would require the installation of transducers at the rear of the trailer. Electrical power must be supplied to the transducers, and signals must be received by the display unit in the cab. This implies that a separate cable and connector will be required between vehicle units. The design would need to account for resistance to possible damage or abuse.

If strain-gauge transducers were used, the signals from them are normally low-voltage and high impedance. While it is possible to use a multi-wire shielded cable to send these signals to the cab for conditioning and processing, experience with on-board weigh scales (Philips 1989) shows that cables of this type require more maintenance than any other component in the weigh scale system. Some alternatives to this arrangement could include signal conditioning at the transducers, along with:

1) sending a high-voltage, low-impedance signal from each transducer to the cab on a separate wire in a multi-wire cable. This approach would minimize environmental problems (moisture in particular) and would reduce the requirement for high-quality connectors between vehicle units.

2) techniques such as multiplexing or placing an FM, pulse code modulation or other similar signal on top of the power supply line could reduce the number of wires required in the RWD cable. However, this benefit would have to be measured against the higher cost of the electronics.

3) using short-range telemetry to transmit the signals from the transducers to the cab is also possible. Relatively inexpensive multi-channel telemetry is available, but consideration must be given to general radio frequency interference and to potential interference between adjacent vehicles equipped with identical devices.

Among the alternatives described above, telemetry has been found to be particularly attractive in on-board weigh scale applications because of its low maintenance requirements (Philips 1989).

It is possible a vehicle speed input to the RWD may be required to satisfy item 13 in Table 4. This could be achieved by placing a separate transducer between the existing speedometer cable and the speedometer itself or by creating an interface to an existing tachograph or anti-lock braking system.

As noted previously, substantial similarities exist between the RWD arrangement described and existing commercial on-board weigh scale systems. Consequently, it is reasonable to assume that the cost of a RWD would also be similar. The current cost of commercial weigh scale systems varies from approximately $4000 to $6000 (Philips 1989). This is clearly well beyond the return-on-investment cost range of $153 to $633 identified in Section 2. This appears to preclude the development of a stand-alone RWD based on the LTR.

The possibility exists, however, that current on-board weigh scale systems could be modified to perform both functions with a relatively small incremental cost. The major difference would be the inclusion of additional signal processing circuitry within the cab-mounted display unit and the addition of appropriate elements, such as buzzers or lights, to provide the warning. A device that combined the functions of an on-board weigh scale system and a rollover warning device would result in a higher return on investment for the owner than could be obtained if the rollover warning device were bought on its own.

4.4 LATERAL ACCELERATION MEASUREMENT

At first glance, it might appear the measurement of lateral acceleration would provide a good indication of the how close a vehicle is to rolling over. The measurement could be made with an accelerometer mounted close to the vehicle's rear-most axle and oriented to measure lateral acceleration. However, the rollover threshold defines the lateral acceleration that causes the vehicle to roll over under a specific loading condition. As indicated in Section 4.1, a rollover warning device needs to be independent of the payload, the CG height and specific vehicle characteristics, such as axle roll stiffness. Thus, a measurement of lateral acceleration would, as a minimum, have to be combined with payload and CG height information for the specific load. Unfortunately, as the CG height is normally quite difficult to measure, a severe constraint exists on the potential accuracy of such a warning device.

Nevertheless, in special applications where the payload and CG height can be well defined, a rollover warning device based on this approach could make use of inexpensive transducers that are relatively simple to retrofit to existing vehicles. One application for this design approach might be on petroleum tank trucks operated at a few specific loading conditions, e.g., full and empty. If necessary, automatic or operator-assisted determinations of the loading condition could generate predefined values of payload and CG height data for the RWD. Operation of the warning device under partial-load conditions would necessitate measurement of the liquid level in each tank followed by a series of

calculations to determine the payload and CG height. At part-load, liquid slosh could be a significant contributor to rollover, but its contribution could not be measured by an accelerometer.

It is important to note that the accelerometer reading will be affected by the roll angle of the surface on which it is mounted relative to the road surface. This relative roll angle will result in an error in the measurement of lateral acceleration due to the component of gravity acting along the accelerometer axis. For a level road, an actual lateral acceleration a_y and a roll angle φ_s, the accelerometer output a_{out} will be

$$a_{out} = a_y \cos\varphi_s + g \sin\varphi_s \qquad (19)$$

where g is the acceleration due to gravity. If, for example, at the onset of rollover the accelerometer mount had rolled to 5 degrees (typical of the trailer chassis), the second term in this equation will have a value of 0.09 g. Since, ideally, the value of a_{out} should be equal to a_y, and typical values of a_y at the rollover warning point may be as low as 0.25 g, the contribution of the second term in the equation will result in a substantial error. If the accelerometer were located on the trailer axle rather than on the trailer chassis, the roll would not normally exceed approximately 2 degrees before rollover was initiated, and the value of the second term would typically be less than 0.035 g. The measurement error would therefore be relatively small, thus better satisfying item 11 in Table 4. However, although this mounting location provides superior measurement accuracy, it also provides a much harsher environment for the accelerometer in terms of shock, vibration and exposure to salt and moisture.

Note that the roll angle error described causes acceleration readings that are higher than the actuals, resulting in a conservative error, so that the resulting rollover warning occurs too early rather than too late. This is not necessarily undesirable. Moreover, it is possible that some predefined correction factor could be used to partially offset the error.

A rollover warning device based on lateral acceleration would be much simpler than one based on lateral load transfer. Unlike the load cells used for LTR measurement, the installation of an accelerometer would not require major modification of the vehicle and could be performed in a very short time. If the use of cabling could be avoided, perhaps through appropriate combinations of battery power, recharging from the trailer lighting system and signal transmission by telemetry, then an accelerometer-based system could meet the portability requirements outlined in item 4 of Table 4. In addition, it is anticipated the cost of such a system would be significantly lower than of an LTR-based system because of the smaller number of transducers and the absence of cables. The requirement for a cab-mounted display unit would remain unchanged from that defined for the LTR-based system, but this does not account for a great proportion of the cost.

In conclusion, it appears that while an accelerometer-based RWD would have limited capability in terms of providing a consistent warning of rollover, it would have significant advantages in terms of cost, ease of installation and portability for those vehicles able to use it.

5.0 EXISTING COMMERCIAL DEVICES

As indicated in Section 4, attempts have been made to produce a commercial rollover warning device. One such device was the "STABE ALERT Stability Monitoring and Alarm System," developed by Roadway Safety Systems, Inc. of Lakeland, Florida, for use on tractor-trailers, tandem combinations and straight trucks of more than 26 feet. A brochure for the system is reproduced in Appendix A. However, the company is apparently no longer operational, and the disposition of the technology is not clear.

The system makes use of inductive front-wheel speed sensors similar to those used for anti-lock braking systems, and strain-gauged-disk load sensors originally described by Barnett and West in 1983. In addition to providing warnings of lateral instability, the system has been advertised as being capable of detecting defective front-wheel bearings, flat tires and broken leaf springs.

As mentioned in the previous section, one way to make a rollover warning device cost-effective is to integrate it with an on-board weigh scale system. One such weigh scale system is being developed by International Road Dynamics of Saskatoon, Saskatchevan (see Appendix B). A feature of this system is the use of transducers that measure individual tandem wheel loads. This is done by measuring the shear stress in the portion of each axle between the suspension attachment point and the brake backing plate. Compared to conventional on-board weigh scale systems with transducers located between the frame and the suspension, the system has the potential for providing a better indication of individual axle and wheel loads. Since accurate wheel load measurements are critical for calculating accurate LTR values for the prediction of incipient rollover, this system could be well suited for integrating with a rollover warning device.

A number of manufacturers produce the more conventional weigh scale systems where transducers are placed between the frame and the suspension. While these also have potential for integration with a rollover warning device, the authors believe that the performance potential is less than for weigh scale systems that monitor the wheel loads at the axle. An extensive evaluation of the performance of these systems was recently reported by Philips (1989), and a list of the manufacturers and distributors of the evaluated systems is contained in Appendix C.

6.0 PROPOSED RESEARCH AND DEVELOPMENT

Based on the results presented in Section 4, the preferred basis for accurate rollover warning would be the vehicle unit load transfer ratio (LTR) (or the associated axle LTR). An LTR-based RWD would be most feasible if it could be produced by adapting or combining it with existing on-board weigh scale technology. In an RWD application, the cab display would be replaced by one that displayed the LTR and sounded a warning according to predetermined criteria.

The suitability of this approach will depend to a great extent on the consistency with which the rollover threshold of various vehicles under different loading conditions can be predicted by combining the LTR approach with existing after-market load cell technology, i.e., load cells that are installed after the vehicle has been manufactured, as opposed to those that must be installed during vehicle manufacturing. A satisfactory RWD must provide a warning in circumstances where it is not perceived by the vehicle operator as giving a false alarm, and where it provides the operator with sufficient time to take corrective action and thus avoid rolling over. The potential of after-market load cells to achieve this goal cannot be reliably assessed without actual vehicle testing.

Section 4 also identified the measurement of lateral acceleration as a potential basis for the detection of incipient rollover. While the predictions of rollover based on this approach are less accurate than those based on LTR, they would possibly be useful under certain circumstances. It is almost certain that a device based on this approach would be less expensive than one based on LTR.

To investigate further the potential of LTR and lateral acceleration as bases for a rollover warning device, the following research and development is proposed:

1) **Identify a Suitable Test Vehicle:**
   The vehicle should provide a test platform whose primary purposes are to identify the potential of on-board weigh scale load cells to predict an accurate LTR and to assess the performance of a lateral accelerometer for the purpose of providing a warning of incipient rollover. It should permit these evaluations under a variety of loading conditions and up to values of LTR that approach rollover. Ideally, the vehicle would be a tractor-semitrailer design with which the rollover threshold could be varied within a significant range.

2) **Select and Install Load Cells and a Lateral Accelerometer:**
   The load cells from an existing on-board weigh scale system would be installed on the vehicle, along with a suitable lateral accelerometer. The signals would be recorded by an on-board data acquisition system installed for test purposes.

3) **Conduct Tilt Table Tests:**
Tilt table tests would be conducted to determine the correlation between the LTR values measured by the weigh scale system's load cells and the LTR values measured with load cell platforms under the wheels of the vehicle. These tests would also provide an opportunity to measure the axle and body roll of the test vehicle and thus determine the roll error introduced into the measurement of lateral acceleration.

4) **Add Additional Instrumentation and Outriggers:**
Accelerometers would be installed at each of the instrumented axles to allow a reasonably accurate on-road measurement of the axle load transfer ratio. The vehicle would also be equipped with outriggers designed to arrest rollover (Billing 1982). For quantifying the test conditions more completely, additional test instrumentation would include additional lateral accelerometers, a gyro platform to measure body roll angle, and displacement transducers to measure the roll angle of the axle relative to the body.

5) **Conduct On-Road Tests at a Test Facility:**
On-road testing would be conducted at a test facility under a full range of loading conditions and would include steady-state lateral acceleration, as well as transient lane-change manoeuvres. After completing the tests, LTR values would be calculated from the wheel force transducer signals, then correlated with those calculated from the on-board weigh scale system transducers. Other goals to be achieved from these tests include:
   - the determination of suitable warning criteria and thresholds;
   - an evaluation of the warning effectiveness in terms of the operator's ability to take action to avoid rollover;
   - an evaluation of the system's performance on rough road surfaces; and
   - an evaluation of an LTR-based RWD's performance compared to that of one based on lateral acceleration measurement.

6) **Conduct Additional Tests with a Double Combination Vehicle:**
If adequate RWD performance can be demonstrated in the above tests, then a second more dynamically-complex vehicle, such as an A-, B- or C-train, should be identified for testing. This would allow an investigation of which axle or axles should be instrumented and how this choice would be affected by the vehicle's loading condition. In addition, the results of these tests would be used to refine further the criteria used to detect incipient rollover.

7.0 CONCLUSIONS

1) A study conducted by Sparks and Berthelot indicated that 22.8% of 661 accidents involving heavy trucks from four fleets operating in western Canada and the northwest U.S. over a four-year period involved vehicle rollover. Of these rollover accidents, only 3.3% were identified as having definitely been preventable by a rollover warning device (RWD). Those classified as potentially-preventable (depending on the performance of the device and of the vehicle operator) accounted for 38.4% of the total. The non-preventable and unknowns accounted for the remaining 58.3%. While the rollover accidents accounted for only 22.8% of the total number of accidents, they accounted for 61.8% of the total damages, 29% of the number of injuries and 28.6% of the number of fatalities.

2) For the vehicles in the Sparks and Berthelot study, the average annual damage per vehicle resulting from preventable rollovers (i.e., preventable by an RWD) was $42. If an RWD could also prevent 25% of the potentially-preventable accidents, then the average annual damage per vehicle that would be prevented by an RWD would rise to $176. If the life of a truck is 5 years and interest rates are 12%, then the economic breakeven cost for an RWD bought with a new vehicle is $633.

3) If every vehicle in the four fleets referred to above had been equipped with an RWD that eliminated all of the preventable rollovers and 25% of the potentially-preventable rollovers, then over the four-year period of the survey the total number of injuries would have been 91 instead of 93, and the total number of fatalities would have been 34 instead of 35.

4) The lateral load transfer ratio (LTR) is a measure able to provide a relatively continuous, normalized indication of how close a vehicle is to rollover, regardless of the vehicle payload and CG location. However, while the LTR is a useful indicator, on-road measurement of it is not trivial. A method is proposed whereby load cells mounted close to the suspension of one or more axles could be used for estimating the LTR that would be sufficient for predicting incipient rollover. While it would be desirable to measure wheel loads for defining the LTR on all axles but the steering axle, priority would be given to the rear-most axles on the vehicle. Signals from the load cells would be transmitted to a cab-mounted display that would process them and provide a suitable warning when required.

5) Because of the similarities between the components of an LTR-based RWD and those of existing on-board weigh scale systems, it is reasonable to expect their costs would also be similar, i.e., in the range of $4000 to $6000 – clearly beyond the amounts identified in item 2. This cost would be particularly difficult for a vehicle owner to justify exclusively for an RWD because the damage costs

referred to in item 2 are relatively intangible. Because of the component similarity, however, it should be possible to develop a system combining both functions at minimal incremental cost. Such a device would result in a higher return-on-investment for the owner than could be obtained if the RWD were marketed on its own.

6) The measurement of lateral acceleration can be used as a limited basis for the prediction of incipient rollover, but predefined lateral acceleration limits would have to be specified for various specific loading conditions. The roll of the vehicle body relative to the road surface will result in an accelerometer output that is higher than the actual lateral acceleration, resulting in conservative warnings of rollover, i.e., one prone to false alarms. One obvious application for an RWD with this design approach might be on petroleum tank trucks, since these vehicles have fairly consistent product densities and relatively easily determined CG locations and heights. An RWD based on the measurement of lateral acceleration would require an accelerometer to be mounted close to the rear-most axle of the vehicle, as well as a cab-mounted display similar to that described for an LTR-based device.

7) Considerations apart from the immediate costs and benefits have been identified. For example, even among vehicles with RWDs that operate as designed, rollovers will still occur; Sparks and Berthelot classified almost half of their rollover accidents as non-preventable by an RWD. That rollovers will still occur to vehicles equipped with RWDs may be of significant concern to manufacturers of these devices because of the risk of litigation. The consequences of an RWD failure from manufacturing defects, faulty installation or poor maintenance are a further concern.

   Another concern involves the reaction of vehicle operators to the devices. Some operators might develop a false sense of security when driving vehicles equipped with the devices, and thus might drive closer to the rollover limit. This could result in a higher rate of "non-preventable" rollovers, which would offset any decrease in the number of preventable rollovers.

   A final consideration is the potential effect of RWDs on the corporate image of large fleet owners able to invest significant amounts of money in the devices. The publicity benefits might outweigh the cost of the RWDs.

8) A follow-up workplan is suggested to investigate the practical potential of the LTR and lateral acceleration measures as bases for prediction of rollover. This workplan would involve equipping a test vehicle with the transducers for each type of measurement and then performing a tilt-table test. The rollover predictions from the transducers would be compared with the vehicle's actual roll performance. If this assessment were positive, then the test vehicle could be modified (with roll-restricting outriggers and

additional instrumentation) for on-road testing at a test facility. Subsequent tests would further establish the performance potential of the LTR and lateral acceleration approaches to rollover prediction and would allow an investigation of the specific prediction criteria.

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APPENDIX A

THE STABE-ALERT STABILITY MONITORING AND ALARM SYSTEM

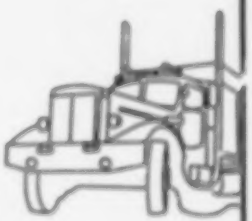
STABE-ALERT®

STABILITY MONITORING AND ALARM SYSTEM

- Helps you drive more safely.
- Helps protect your vehicle.
- Can possibly assist in identifying excessive front wheel drag caused by a defective bearing.
- Notifies driver if flat tire has occurred or if he/she has a broken leaf spring.
- Helps reduce your risk of accident and most importantly, could possibly save lives.

FOR USE ON:

Liquid, Petroleum, Chemical, Cargo, Cryogenic, Flat Bed and all general Tractor/Trailer and Tandem Truck combinations. May also be used on straight trucks with a minimum length of 26 ft.



ROADWAY SAFETY SYSTEMS, INC.

1-800-882-7790

THE SYSTEM

The *STABE-ALERT®* control unit utilizes state-of-the-art microprocessor based technology to provide the ultimate product reliability and performance.
Features include an advanced switching power supply allowing the system to operate on 12 to 24 volts, positive or negative ground electrical systems without modification.

The *STABE-ALERT®* unit has been developed using the latest low power, CMOS circuit technology to reduce power consumption and enhance reliability under all operating conditions.

STABE-ALERT® unique sensors offer the ultimate in performance and immunity to external factors even in the worst operating conditions.

The *STABE-ALERT®* system undergoes stringent quality control checks during every step of its manufacture and is unconditionally guaranteed, parts and labor, for a period of three (3) years from date of purchase. (See Warranty Policy for details.)

FEATURES

- Ease of operation.
- Ultimate reliability.
- Environmentally sealed sensors.
- Environmentally sealed cables.
- Utilizes 12 to 24V power without electrical modification.
- Simple installation (approx. 4 hrs.).
- 36-month warranty on materials or workmanship.
- Advises the driver if he/she has a flat tire, broken leaf spring or front wheel that is dragging because of bearing problem.

APPLICATIONS

Liquid Petroleum	Grain Haulers
Liquid Chemical	Log Trucks
Cryogenic	Steel Haulers
Flat Bed	Liquid Food Tankers
Dry Freight	Bulk Commodity Haulers
General Cargo	Heavy Equipment Carriers
Produce Haulers	Specialized Cargo Vessels
Livestock Haulers	Explosives Delivery Trucks

TECHNICAL SPECIFICATIONS

FRONT SENSORS PERFORMANCE SPECIFICATIONS:

Housing: Crastin, water resistant and corrosion proof. The solid state components are embedded in an epoxy resin under vacuum and the cap is ultrasonically welded to the body. This construction assures watertight integrity and prevents condensation. Crastin sensors may be immersed in water up to + 158° F without damage to the sensor.
Nema Rating: 1, 2, 3, 3R, 4, 4X, 5, 6, 6P, 12, 13
Ambient Temperature: – 40° F to + 212° F
Approval Standards: UL, FM and CSA approved.

REAR SENSORS PERFORMANCE SPECIFICATIONS:

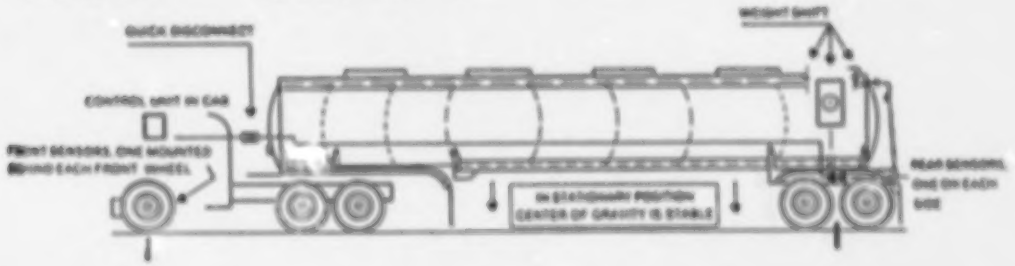
Housing: Stainless Steel construction, hermetically sealed, corrosion resistant, field installable into existing suspension systems.
Temperature Range: – 40° F to + 160° F
Approval Standards: FM approved as CLASS 1611, XJYI.

CABLE SPECIFICATIONS:

All cable is weather proof, corrosion and oil resistant. Enough cable is provided with system to wire standard tractor/tractor. Custom tractors with enlarged sleeping compartment and tandem trailers must be specified.

CONTROL BOX PERFORMANCE SPECIFICATIONS:

Housing: Aluminum with graphic display board and spectra color L.E.D.'s.
Dimensions: Inch(Mm)
6.650 x 5.120 (16.891 x 13.004)
Power Requirements: 10 to 30V (12 to 24 nominal). Positive or Negative ground, intrinsically safe.
Operating Temperature: – 40°F to + 140°F
Response Time: 3 seconds. Circuit is completely self-checking and is fail-safe, keeping the driver notified at all times as to operational condition of complete system.
Approval Standards: Pending FM and CSA approval.



"Our Customer Service Department is always ready to answer your application and installation questions on our Toll-Free Sales and Service Hot Line: 1-800-882-7790 and 24 hrs. Fax Line: 613-647-3338"

TRACTOR

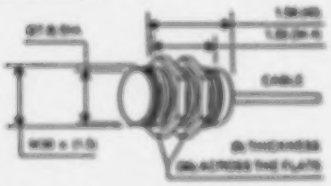
The front wheel stability is monitored by two electro, weather sealed and corrosion-proof inductive proximity sensors that count pulses as permanently mounted targets pass in front of the sensor force field when the wheels are spinning.

The rate at which the right and left wheel respectively are spinning is compared for the degree of synchronization. The circuit counts and compares consecutive pulses from both sensor inputs in various numbers of measuring cycles.
A bad bearing will also cause a certain percentage of desynchronization. If this offset is severe enough, it will cause the wheel to drag and the **STABE-ALERT®** will alarm and advise the driver accordingly.

FRONT SENSORS

Located on right and left wheels provide input signals to synchronization comparitor circuit located in control unit.

DIMENSIONS: Inch(mm)



FRONT SENSING PLANE

Is located behind wheel as shown on detail below.
Adjustable adaptor located on grease fitting holds sensor that looks at target mounted on brake drum (target mounting location differs on vehicles with disc brakes).

TRAILER

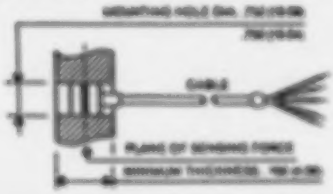
The rear stability sensors monitor the side and downward strain as conditions remain safe or change over the road. The units will sense side to side sloshing and metal strain as weight becomes unevenly distributed. The output signal of both, front and rear sensors, are integrated and analyzed in the **STABE-ALERT®** unit on the dash board.

In addition, if a flat tire begins to occur, a gradual weight shift will result causing the **STABE-ALERT®** to go into alarm. A broken leaf spring will show an immediate alarm condition.

REAR SENSORS

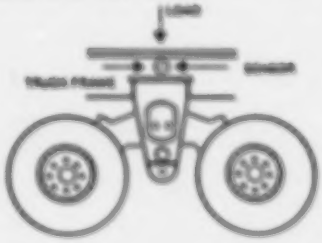
Located on right and left wheels provide proportional side to side strain and weight shift signal to control unit.

DIMENSIONS: Inch(mm)



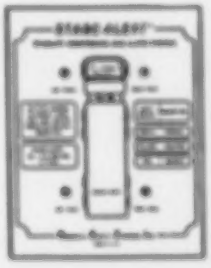
REAR SENSING PLANE

Is located in frame of trailer as shown on detail below.
Sensor is press fit into precision hole making it integral to frame of the trailer. (Sensor location varies on different model trailers. See Instruction Manual for details).



CONTROL BOX...

Mounts on dash board or overhead. (See Instruction Manual for details).



APPENDIX B

THE INTERNATIONAL ROAD DYNAMICS ON-BOARD WEIGH SCALE SYSTEM[2]

[2] Reproduced from: Research and Development Bulletin, June 1990, published by Science and Professional Services Directorate of Supply and Services Canada.

RESEARCH AND DEVELOPMENT

Lightening the load

Technology developed by International Road Dynamics (IRD) of Saskatoon may help make overweight vehicles and the damage they do to Canada's roads a thing of the past.

Working under a $309,040 contract funded jointly by Supply and Services Canada and Transport Canada, IRD developed and produced a sensor capable of determining the weight carried by an individual truck axle. A driver can receive an overweight ticket if even one axle of the truck is carrying more than the allowable weight.

Unlike a home bathroom scale, which both measures and bears weight, the on-board scale developed by IRD measures the weight of the vehicle without bearing any of that weight.

In previous on-board weigh systems, load cells were mounted between the truck's frame and suspension. Every bump in the road brought the weight of the truck to bear on the device, and trucking companies paid for this abuse in high maintenance costs.

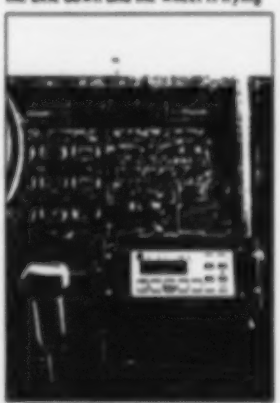
"The nice thing about our system," says IRD president Terry Bergan, "is that it is mounted directly onto the axles and the frame of the truck."

The device, like a thermometer in a jogger's mouth, is simply along for the ride. This unique feature means that the IRD system not only costs substantially less to maintain, but also costs less to install. In fact, installation costs for the new system are about half what they were for the old.

"If you have to get into a truck's suspension," says Bergan, "you have to tie up a hoist and the truck. Our equipment is welded on. You don't have to modify the suspension or any of the components of the truck."

The new system measures sheer stress, not weight, according to Lewis Sahoungbi, a project officer with Transport Canada's Transportation Development Centre (TDC) and the project's Scientific Authority.

"Visualize the axle of a truck as many vertical planes, one next to the other, and stuck to each other. The weight of the truck is trying to push the axle down and the wheel is trying to hold the axle up. So there is a region of the axle between the wheel and the suspension that is transmitting the weight of the truck from the suspension to the wheel. This region develops what is called a sheer stress. It is this sheer stress in the axle that we are measuring."



A microprocessor in the truck's cab analyses the data and displays the results. (Photo courtesy of International Road Dynamics)

The load cell looks like a small piece of metal. "We take a piece of steel," says Terry Bergan, "mill out the edges so it reacts with the axle properly, drill a hole into it, mount the instrumentation in the hole, and then cover it with tar."

The tar seals the equipment, keeping out moisture and salt. The instrumentation sends an electric charge through the metal. When the charge encounters sheer stress, the instrument measures the change in the electricity. The greater the sheer stress, the greater the change in the electric current.

A microprocessor in the truck's cab analyses the data and displays the results. The display indicates the individual axle weights and the gross vehicle weight, allowing the driver to maximize loads while avoiding overweight tickets.

Without the information provided by the IRD display, even though an experienced driver could be right about the total vehicle weight, he could still be wrong about the axle-by-axle distribution of that weight.

If a microprocessor is mounted on the chassis of the truck, the data can be transmitted by radio to a display on a forklift. This allows an operator to load a truck in the absence of the driver. ■

The instrumentation sends an electric charge through the metal. When the charge encounters sheer stress, the instrument measures the change in the electricity. The greater the sheer stress, the greater the change in the electric current. (Photo courtesy of International Road Dynamics)

continued from page 5

TDC is involved in the project in an attempt to extend the life of Canada's road network by minimizing the punishment that the network takes from overweight vehicles. IRD estimates that five percent of the highway vehicles in Canada will be using the new technology within its first two years on the market. In the long run, about the only highway vehicles unlikely to use the technology are those hauling fluid loads, such as milk. The drivers of those vehicles simply meter the fluid as they load their vehicles.

TDC's other goal was to help develop a Canadian product for the export market. IRD estimates that one percent of the highway vehicles in the United States would be using their product within two years of bringing it to the U. S. market.

APPENDIX C

MANUFACTURERS AND DISTRIBUTORS OF ON-BOARD WEIGH SCALE SYSTEMS REVIEWED BY FERIC (from Philips 1989)

Brand Name	Address of Distributor
Lodec (Electronic load cell)	Lodec Electronic Scales 19416 - 94th Avenue Surrey, B.C. V3T 4W2
	Équipment Cot Kurb Inc. 720 Rue St.-Jacques St.-Jean sur Richelieu Quebec J3B 2M7
Structural Instrumentation (Electronic load cells and transducers)	S.I. Electronic Weighing Systems 120 - 1765 Springfield Road Kelowna, B.C. V1Y 5V5
	Les Balences S.I. Quebec, Inc. Box 396 Valdor, Quebec J9P 4P4
Vulcan (Electronic load cell)	Canadian Stress-Tek 5437 Dominion Street Burnaby, B.C. V5G 1E1
Williams (Air lift-pad scales)	Williams Air Controls (Dana Corp.) 14100 S.W. 72nd Avenue Portland, Oregon 97224
Smieja (Hydraulic lift-pad scales)	Fab-Tek Inc. 16432 S.W. 72nd Avenue Portland, Oregon 97224

REPORT DOCUMENTATION FORM/FORMULAIRE DE DOCUMENTATION DE RAPPORT

REPORT No./ NO DU RAPPORT 1 TR-VDL-005	REPORT No./ NO DU RAPPORT 2	SECURITY CLASSIFICATION/ CLASSIFICATION DE SÉCURITÉ 3 ___ Top Secret/Très secret ___ Secret ___ Confidential/Confidentiel ___ Protected/Protégée _X_ Unclassified/Non classifiée
DISTRIBUTION/DIFFUSION 4 ___ Controlled/Controlée _X_ Unlimited/Illimitée		

DECLASSIFICATION: DATE OR REASON/DÉCLASSEMENT: DATE OU RAISON
5

TITLE, SUBTITLE/TITRE, SOUS-TITRE

6 A Feasibility Study of a Rollover Warning Device for Heavy Trucks

AUTHOR(S)/AUTEUR(S)

7 J. Preston-Thomas; J.H.F. Woodrooffe

SERIES/SÉRIE

8 Technical Report

CORPORATE AUTHOR/PERFORMING ORGANIZATION/
AUTEUR D'ENTREPRISE/AGENCE D'EXÉCUTION

9 National Research Council of Canada
Institute for Mechanical Engineering

SPONSORING OR PARTICIPATING AGENCY/AGENCE DE SUBVENTION OU PARTICIPATION

10 Transportation Development Centre, Transport Canada

DATE	FILE/DOSSIER	SPECIAL CODE/ CODE SPÉCIALE	PAGES	FIGURES	REFERENCES
11 09/1990	12	13 23300	14 33	15 6	16 11

NOTES

17

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

18 heavy trucks; rollover; rollover warning device

SUMMARY/SOMMAIRE

19 Assessment of technical feasibility of a device to warn operators of heavy trucks of incipient rollover.

ADDRESS/ADDRESSE

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Vehicle Dynamics Laboratory
Institute for Mechanical Engineering
Montreal Road, Ottawa, Canada
K1A 0R6 (613) 993-2425

Revised 08.1990